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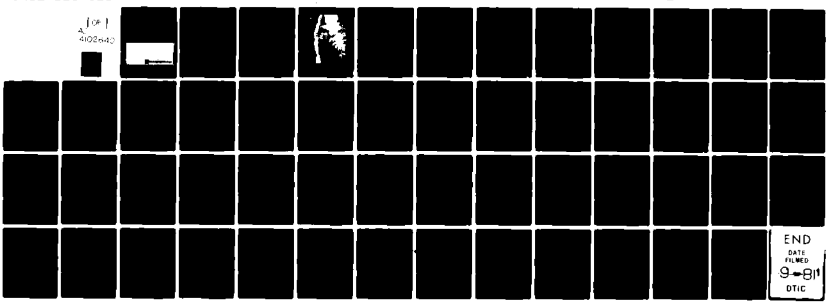

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GEOTHERMAL RESOURCE VERIFICATION

FOR AIR FORCE BASES

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Philip R. Grant, Jr.
Energy Resources Exploration, Inc.

Sandia National Laboratories

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GEOTHERMAL RESOURCE VERIFICATION

FOR

AIR FORCE BASES

SAND81-7123

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Abstract

Geothermal energy offers a potential alternative to oil and gas for supplying the stationary energy requirements of military installations. However, because of the past dominance of oil and gas, procedures for estimating geothermal energy potential have not been well defined nor well tested.

This report summarizes the various types of geothermal energy, reviews some legal uncertainties of the resource and then describes a methodology to evaluate geothermal resources for applications to U.S. Air Force bases. Estimates suggest that exploration costs will be \$50-300,000, which, if favorable, would lead to drilling a \$500,000 exploration well. Successful identification and development of a geothermal resource could provide all base, fixed system needs with an inexpensive, renewable energy source.

Frontispiece: Landsat image of Albuquerque-Kirtland [illegible]
New Mexico. Scale 1:250,000. Black [illegible]
of a portion of enhanced color [illegible]
(Available from EROS Data Center, [illegible]
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INTRODUCTION

No point on earth is more than about 20 miles (32 km) from what is essentially a perpetual heat source with temperatures approaching 2[illegible] (1093°C). This is the magma or hot plastic mantle upon which the relatively thin plates of solid rock forming the planet's crust [illegible]. Existing technology developed by the oil industry is capable of [illegible] 6 miles (10 km) with the drill bit, but at considerable expense. Development and utilization of a geothermal resource, then, depends upon encountering it at reasonable depths with certain physical parameters that assure its sustained use for a particular application.

In many regions of the world, including the western United States, the heat source is closer to the surface than in areas where the crust [illegible] thicker. In these places the heat from this enormous reservoir, a [illegible] of billions of years of decay of radioactive minerals, flows to the [illegible]face and may dramatically appear in highly visible and spectacular [illegible] as volcanoes, geysers and hot springs. Other geothermal regimes are [illegible] so obvious and may manifest themselves as higher than normal underground temperatures that must be searched for using conventional and special [illegible] exploration techniques. In some regions where thick sedimentary basins occur usable hydrothermal resources may be encountered in deep wells where there is no abnormal thermal anomaly; the hot water is merely a function of normal temperatures that increase at depth.

The world "geothermal" simply means "earth heat." Geothermal energy, then, is the heat generated in the interior of the earth and conducted to the earth's surface. Harnessing and use of the natural heat of the earth may, in some cases, be the lowest cost and longest lasting fuel system available, as well as a form of energy that can be applied with minimum of adverse environmental problems.

Geothermal applications with tremendous potential for reducing dependence on conventional fuels and foreign suppliers appear in two broad forms [illegible] may or may not compliment one another. The first is for generating electricity from water supplies indigenous to subsurface rocks or which may be introduced to them that are hot enough to become steam at atmospheric pressure to turn a turbine; or hot enough to heat a substitute fluid that, when vaporized, may operate in a closed system to drive a turbine. If extensive, a high temperature geothermal resource may be economically attractive even if located in a remote area because its primary product, electricity, can be moved great distances to a point [illegible] use.

The second, potentially most attractive and economically rewarding [illegible] is for "district heating" and other nonelectric applications that include space heating and cooling, industrial process heat and agricultural uses. Low and moderate temperature geothermal regimes usable in direct applications are simply waters of lower temperatures than required for electricity generation. "Spent" high temperature water available immediately after its use to generate electricity is in[illegible] (Multiple use of the primary geothermal resource is called cascading. The secondary applications are "congenerating" uses.) Generally, [illegible] use or application of low and moderate temperature resources must be made near their geographic/geologic occurrence, since the primary product, heat, cannot be economically transported significant dist[illegible]. Ideally, flowing hot water which is clean and potable would be encountered in or near a populated or developed area where there [illegible] be multiple use of the resource.

OBJECTIVES

There is abundant evidence that geothermal energy offers an outstanding alternative to the country's continued dependence on conventional fuels. Free of foreign influence and interference, comparatively benign environmentally, relatively non-exotic in the context of development and applications, almost ubiquitous in terms of occurrence and, when used to generate electricity, offering greater flexibility than most other fuels as well as multiple use of its heat, the nation's geothermal resource is an extraordinary asset for fulfilling a commitment of energy self-sufficiency.

The Department of Defense is under the same mandate as the rest of the federal sector to conserve energy, switch to alternate fuels, and apply advanced energy technologies. The U.S. Air Force has recognized the potential for using geothermal resources in lieu of conventional fuels as a tactical and strategic goal [Austin and Whelan (1978)], and a practical objective [Barattino (1979)].

Attempts to identify and develop geothermal resources on certain Air Force properties are currently underway. Investigations conducted at Williams Air Force, Arizona, conclude that conditions appear very good to develop a 350°F (176°C) hot water reservoir in fractured volcanic rocks at a depth of about 10,000 ft (3 km) [EG&G Idaho, Inc. (1979)]. Options for applying this resource if development efforts are successful range from generating electricity to space cooling and heating, suggesting that the base could become self-sufficient for its non-transportation energy needs. An apparent unsuccessful effort to locate a low to moderate temperature hydrothermal regime suitable for space heating at Hill Air Force Base, Utah, was recently completed and described [Glenn, et al., (1980)]. Other on-going Department of Defense sponsored geothermal projects include developing electrical generating capacity at China Lake Naval Weapons Center, California; Adak Naval Station, Alaska; and Fallon Naval Air Station, Nevada. Space heating capabilities are being examined or constructed at Keflavik Naval Station, Iceland, and Norfolk Naval Station, Virginia [Interagency Geothermal Coordinating Council (1980)].

The primary purpose of this report is to describe methodologies for verifying a geothermal resource on Air Force installations. The assessment includes descriptions of geothermal occurrences and will address various techniques used in exploring for the resource. These methods are not unique to a site-specific Air Force base, but will similarly apply to a broader range of properties. This methodology is designed to provide those authorities charged with the responsibility to develop and assess an exploration program, but who may lack specific geothermal expertise and a background in the earth sciences, a basis to design, propose, conduct and evaluate an exploration program for geothermal resources.

CHARACTERIZING GEOTHERMAL RESOURCES

Defining the Resource

The U.S. Geological Survey defines geothermal resources as "stored ... both identified and undiscovered, that is recoverable using current ... near-current technology, regardless of cost" [White and Williams ...]. Although this satisfies many technical requirements, it should be recognized that there is presently no consistent, legally acceptable definition of a geothermal resource. Whether the resource is subject to ... law or mineral law is the subject of considerable conflict.

Some 15 states and the federal government have statutorily defined a geothermal resource, although not always in the same manner. Depending upon constituent interests legal definitions range from calling the resource water (Nevada, Wyoming, Utah), a mineral (Hawaii), and sui generis (Idaho, Montana, and Washington) which bears a legal connotation implying that the resource is "of its own kind or class or not necessarily a mineral or water" [Maley (1979)]. Other states have attempted a ... tion which treats the resource as a mineral for leasing and revenue purposes while trying to save harmless the water rights. Where the complexities of the geothermal resource have been addressed by the ... [Pariani vs State of California, on appeal, 1st Appelate Dist., ... Case 47185; Geothermal Kinetics vs Union Oil, 75 Calif. App. 3d 5..., 141 Cal. Rptr. 879 (1977); United States vs Union Oil Company of ... 549 F. 2d 1271 cert. denied, 98 S. Ct. 121, (1977)], the issue has generally been decided in favor of defining a geothermal resource as ... mineral [Grant (1979)].

Defining any resource is difficult. Defining a geothermal resource ... the conventional manner of identifying all its parts and assigning ... categories that logically lend themselves to beneficial use, income, regulation, royalties, protection and non-infringement of other ... resources, etc., as well as categorizing its geologic parameters ... be possible. A geothermal resource may, at one and the same time, ... liquid, gas, solid and a mineral. Individually or collectively with ... further refinement, none of these relate to the desirable product, ... heat. By themselves they are either the heat transporting medium that must be "borrowed" to place the contained heat content (enthalpy) ... it can be used, or the heat generating and storage facility that ... discovered and exploited in some manner to release its heat.

For purposes of this report, in the exploration context, geothermal resources are defined as the recoverable heat of the earth that may ... converted to useful energy. This has the advantage of clearly ... that heat is the element being searched for.

Geothermal Resources and Conventional Fuels, Comparisons

In concluding that geothermal resources are legally a mineral, the courts relied to a large extent on comparisons of the production ... geothermal energy from the vapor-dominated steam system at The Ge... in California to the production of energy from "such other minerals ... coals, oil and natural gas in that substances containing or ... producing heat are removed from beneath the earth" [Geothermal Ki... In the broad sense of being capable of producing energy, geothermal resources are like conventional fuels. There are differences worth noting, however, that are important in exploration and development ...

It is generally accepted that in a non-technical sense oil, gas and coal are "conventional" fuels that are combustible. A geothermal "fuel" is considered an "alternative" fuel and is non-combustible. A lighted match introduced to an open container of oil, flow of natural gas, or lump of coal produces an expected, predictable, generally measurable and significantly different energy effect than the lighted match dropped into a column of hydrothermal water or a fluid magma would produce.

On the other hand, unlike other fuels, geothermal energy can be used directly without combustion or fission to produce usable heat. Geothermal energy is also considered a renewable resource, unlike conventional fuels which are finite. Even if a geothermal reservoir is depleted of its thermal values or heat transfer medium by production, given time it will probably restore itself if the storage area was not damaged. Once produced and consumed by combustion, oil, gas and coal are forever lost.

Like oil and gas, geothermal fluids are "fugitive" in that they migrate freely through pore spaces with permeability. Their focal point for production requires a storage area that is hot, either in the rock itself or in an aquifer connected to a heat source. Many of the analogies end at this point, however. Unlike oil and gas (and coal), a geothermal resource cannot be removed from its primary storage and be contained elsewhere awaiting use. It is, therefore, site-specific in terms of how, where, and for what purpose its indigenous heat may be used.

Classification of Geothermal Resources

Overview -- Geothermal resources are diverse in occurrence and do not lend themselves to orderly generic classifications that can be agreed upon by most investigators. In a broad sense, there are only two kinds of geothermal systems: those that contain indigenous water in a porous and permeable host rock (convection systems), and those that do not (conduction systems). In a more restricted and specific context, there are numerous variations, modifications and combinations within the major classifications.

In an emerging natural resource oriented technology this is not unusual. It is comparable to classifying hydrocarbon trapping systems. In the broad sense oil and gas accumulations are either structurally or stratigraphically controlled. Structural traps may be refined to incorporate mechanisms occurring in nature that fold, fault or fracture a potential reservoir rock. Stratigraphic accumulations may occur as a result of a facies change, unconformity, change in hydrodynamic gradient, etc., within the reservoir rock. In addition, combinations of these parameters may result in trapping situations where individual parameters would not. Most of the important geothermal accumulations currently under investigation result from a combination of heat conduction and convection systems, modified by many of the same geologic parameters influencing oil and gas traps.

Knowledge of geothermal resources is rapidly expanding from the limited base that existed prior to 1973's Middle East oil embargo; however, until most of the major components of geothermal systems are identified and additional experience permits their predictability with some confidence, it may be difficult to develop a more detailed classification. In the interests of simplicity and some uniformity, the classification system used in this report is adapted from the USGA [White and Williams (1975)].

Hydrothermal Convection Systems -- The earth's usable or recoverable heat is stored or contained exclusively in the rocks of the crust. The medium that makes this heat available for use is almost exclusively water. In hydrothermal (hydro=water, thermal=heat, i.e., "hot water") convection systems, the water occurs naturally in connected voids in the rock. The voids may be intergranular, faults, fractures or [illegible] cavities and are termed pore space. Their interconnection permits movement of fluids is called permeability. Convection occurs in rocks of adequate permeability because of the buoyancy effect of heat and consequent thermal expansion of fluids in a confined or partially confined system. Cold water enters the system from the atmosphere and is circulated downward to a heat source in the rock. When it is heated it is less dense than when it was cold, causing it to rise near the surface, where it may become concentrated in a reservoir [illegible] conditions attractive tc exploit. The USGS describes two categories of hydrothermal convection systems.

Vapor-dominated Sub Systems

These are the rarest naturally occurring geothermal regimes. Those so far discovered in the U.S. are characterized by surface steam vents found in areas of geysers. Besides occurrences at Yellowstone and Mt. Lassen National Parks, which are withdrawn from geothermal resource development, the only other vapor-dominated system encountered in the U.S. is The Geysers of California. There is some evidence that the hydrothermal resource being developed in the Valles Caldera of New Mexico's Jemez Mountains may contain a vapor-dominated component [DOE (1980)].

Vapor-dominated reservoirs produce superheated steam with minor amounts of other gases such as hydrogen sulfide and carbon dioxide at temperatures around 464°F (240°C), with little associated water. Hence, the concept of an all steam of "dry" steam reservoir. The steam can be used directly from the well into the turbine after passing through particle separators.

The vapor-dominated regime is a unique, geologically infrequent, and very small part of the much more extensive hydrothermal convection system of geothermal energy. Yet, because it is the most well known and is readily identified with the only commercial geothermal venture in the U.S., The Geysers in California, it has become associated by some without expertise in resource assessment as representing the full range of geothermal resources. Many unduly stringent laws and regulations govern the exploration, development and production of all geothermal resources as a result of this narrow perception. Instead of being considered a routine part of a broad energy mix, The Geysers association and environmental oversight requirements applied to it suggest to many that geothermal occurrences are complex, technologically untested, and exotic phenomena. Focus on this geological exception has, to some extent, unnecessarily inhibited the exploration and development of potentially more extensive and valuable geothermal regimes with electrical and direct heat applications.

Hot Water Subsystems

Many hot water systems are readily identified by the occurrence of hot springs. Examination of the chemical composition of hot spring waters, their aerial distribution, and associated hydrothermal alteration of contiguous rocks sometimes yields useful information to characterize subsurface conditions of temperature, volume, source, etc. If the ground water table does not intersect the land surface, or if the hydrothermal reservoir is confined by impermeable rocks, there may be little or no direct evidence of the resource, requiring the use of a range of relatively simple and low cost to ingenious and expensive exploration techniques to locate it.

Any surface or ground water regime with above normal or ambient temperatures for the area is a geothermal resource. The USGS [White and Williams (1975), Muffler (1979)] describes hot water systems with temperatures that range up to 680°F (360°C) in the Salton Sea, California, and the nearby Cerro Prieto region of Mexico. Liquid water can exist underground in nature to a maximum temperature of 705°F (374°C), regardless of reservoir pressure, so the Imperial Valley reserves represent the upper limit of hot water systems. USGS further characterizes hydrothermal regimes in terms of their implied applications by dividing them into temperature ranges.

1) Water with temperatures above 302°F (150°C) are systems that may be considered for generation of electricity. Wells that encounter water at depth with temperatures that are greater than surface boiling temperatures produce water with a steam increment. The all-important steam ratio is dependent upon temperature and, if circulated through a steam-water separator to divert the steam to a turbine, the pressure in the separator. At 50 lb/in^2 (4.46 bars), 572°F (300°C) water yields 33 percent steam; 392°F (200°C) yields 11 percent; while 302°F (150°C) gives up no steam (at 50 lb/in^2 pressure). The rationalization for determining the practical cut-off point for a hot water subsystem for generating electricity from flashed steam at 302°F (150°C) is readily apparent. Binary systems that use hot water in a closed loop to heat a medium with a lower flash-point temperature can use lower temperature water, however.

2) Water with temperatures ranging between 194°F and 302°F (90°C to 150°C) is usable in direct heat applications and, with heat exchangers, space cooling.

3) Water with temperatures below 194°F (90°C) can be used in local, specialized applications for space heating and industrial process heat.

All of the known hydrothermal convection systems in the U.S. with temperatures above 194°F (90°C) occur west of the east face of the Rocky Mountains. Their distribution by geologic province is illustrated in Figure 1. USGS [Muffler (1979)] indicates that the heat energy contained in identified systems is 2,900 x 10^{18} joules = 1 quadrillion Btu's). Hot water systems in these provinces remaining to be discovered are estimated to contain an additional 8,000 quads of energy. These geothermal energy relationships are described in Table 1.

No intermediate to high temperature hydrothermal reservoirs have been found east of the Rockies. Although this part of the continent encompasses a diversity of geologic environments, the relatively stable tectonic setting, normal heat flow, and absence of recent volcanic activity may preclude their occurrence. However, USGS [Muffler (1979)] states that based upon information obtained on low temperature thermal waters (under 194°F/90°C), "a perhaps unexpected resource exists in parts of the Central and Eastern United States. On the basis of this assessment, <u>low-temperature thermal waters appear to constitute one of the most widely available energy sources in the nation</u>" (emphasis added).

<u>Hot Igneous Condition Systems</u> -- These are systems that utilize the heat that occurs naturally in all the earth's rocks, including molten magma, usually with an assist by introducing water from an external source.

<u>Magma or Molten Rock Subsystem</u>

Of all the categories of geothermal resources, those with molten magma at temperatures above 1202°F (650°C) and ranging up to 2192°F (1200°C) contain the most stored heat per unit of volume or mass. The technological problems of utilizing this primary heat source are the most difficult of all.

The objective of the Magma Energy Research Project at Sandia National Laboratories, a program of the U. S. Department of Energy, is to investigate the scientific feasibility of extracting energy directly from deeply buried circulating magma sources. Recent results suggest that boreholes will remain stable down to magma depths, engineering materials can survive the downhole environments, and energy extraction rates are encouraging [Colp (1980)]. Additional research is necessary, however, to determine the practical feasibility of extracting energy from the ultimate geothermal source, the magma body.

Geologically large and young magma systems are especially attractive targets for current exploration, however. This interest is not necessarily for the development of direct magma heat transfer processes, but because their existence accounts for the largest number of favorable high temperature water convection systems in association with them.

<u>Hot Dry Rock Subsystem</u>

A hot dry rock geothermal resource occurs where near surface, usually crystalline (granite) rocks are hot, but a natural "plumbing" system containing water is absent. The process involves drilling into the hot formation and hydraulically fracturing the reservoir by injecting cold

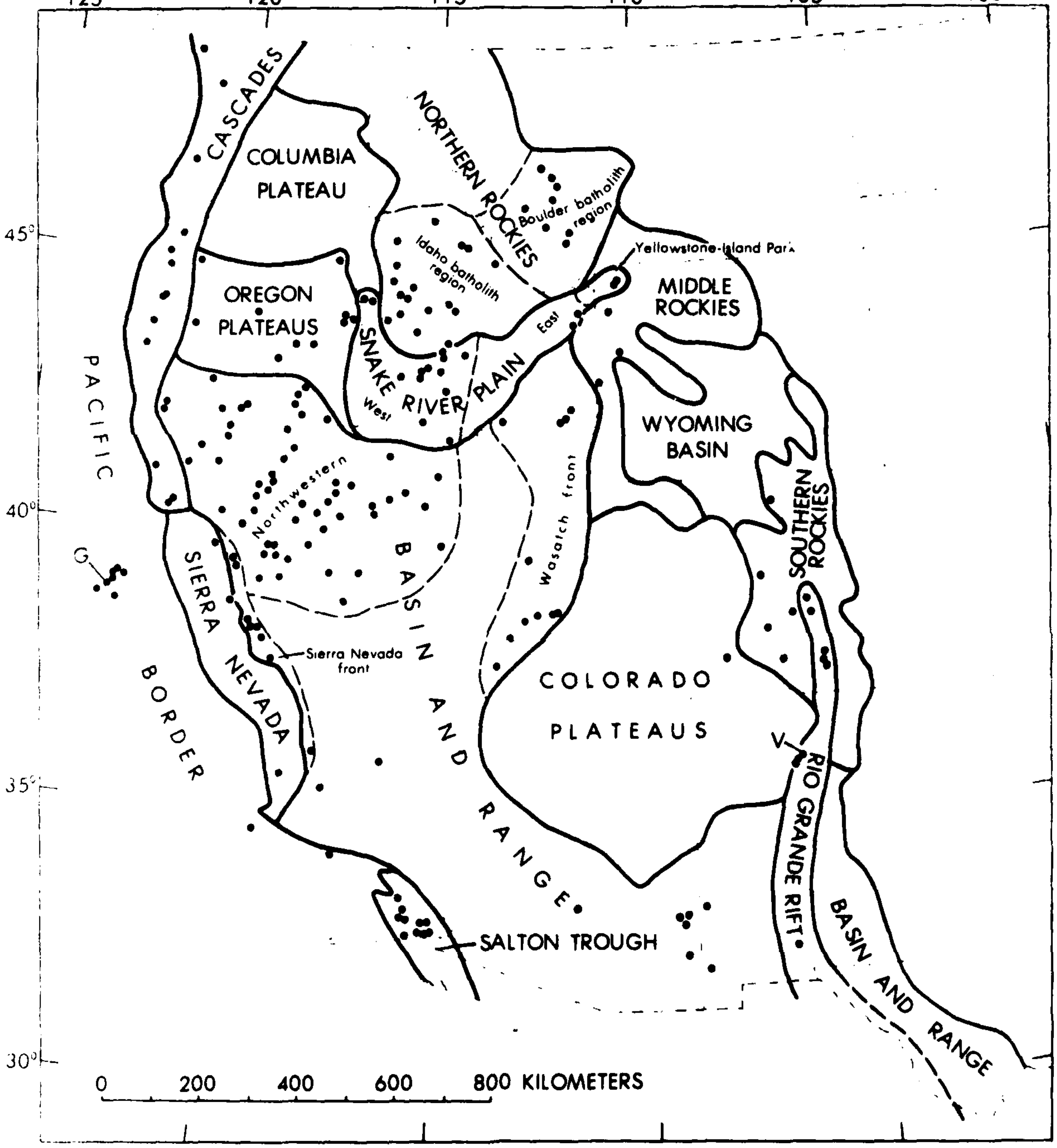


Figure 1. Map of geologic provinces of the Western United States. (Dots indicate locations of identified hydrothermal convection systems with reservoir temperatures $\geq$ 90°C. G = The Geysers; V = Valles Caldera.) [USGS, Muffler (1979)]

Table 1. Summary of the identified and undiscovered accessible resource base for geologic provinces of the Western United States (Province boundaries are shown in Figure 1. Identified component includes energy in National Parks.) [USGS, Muffler (1979)]

Province	Accessible Resource base ($\times 10^{16}$ J) Identified	Undiscovered
Pacific Border		
The Geysers-Clear Lake area	150	150
Other	3	15
Cascades Mountains	57	1,140
Sierra Nevada Mountains	5	5
Columbia Plateau	0	0
Oregon Plateaus	80	400
Snake River Plain		
Western		
Central and southwest	470	940
Camas Prarie and northern margin	21	100
Eastern	21	1,520
Yellowstone-Island Park	1,240	170
Basin and Range		
Northwestern	280	1,400
Sierra Nevada front	120	40
Wasatch Front and northeastern margin	67	170
Other	12	60
Salton Trough	240	480
Rio Grande Rift		
Valles Caldera area	87	87
Other	6	60
Colorado Plateaus	1	50
Rocky Mountains		
Idaho Batholith	14	70
Boulder Batholith	11	55
Middle Rocky Mountains and Wyoming Basin	2	10
Southern Rocky Mountains	5	2[illegible]
Alaska		
Alaska Peninsula and Aleutian Islands	10	580
Central Alaska	11	220
Southeast Alaska	10	100
Other	0	100
Hawaii	9	45
TOTAL	2,900	8,000

water into it under pressure to create an extensive fracture system at depth. Once the reservoir is fractured, a second well is drilled nearby to intersect the fracture zone. Cold water from a surface source is introduced into one well, heated during its passage from the fractured thermal area, and withdrawn as hot water or steam from the second well.

Los Alamos National Laboratory (LANL) has been involved in research and technology into hot dry rock geothermal systems since 1970. At a site at Fenton Hill in the Jemez Mountains of New Mexico, LANL has drilled two holes in granite some 250 feet from each other to depths of 9,610 ft and 10,053 ft. Bottomhole temperatures were 387°F (197°C) and 402°F (206°C). The two holes were successfully interconnected, and in June 1977 the system was tested by pumping cold water down one well and recovering it at the surface in the other well at a temperature of 266°F (130°C). In March 1980 the process was successfully used to produce 60 kilowatts of electricity (kWe) in a binary system using the hot water to vaporize Freon (R114) to drive a turbine. In May 1980, a third well was completed at the site to a depth of 15,289 ft and a fourth well is being drilled. The objective is to encounter and utilize substantially higher temperatures with which to demonstrate commercial electrical generating capabilities with a range of 4-10 MW [LANL (1980); Kaufman and Sicilian (1979)].

Combination Systems

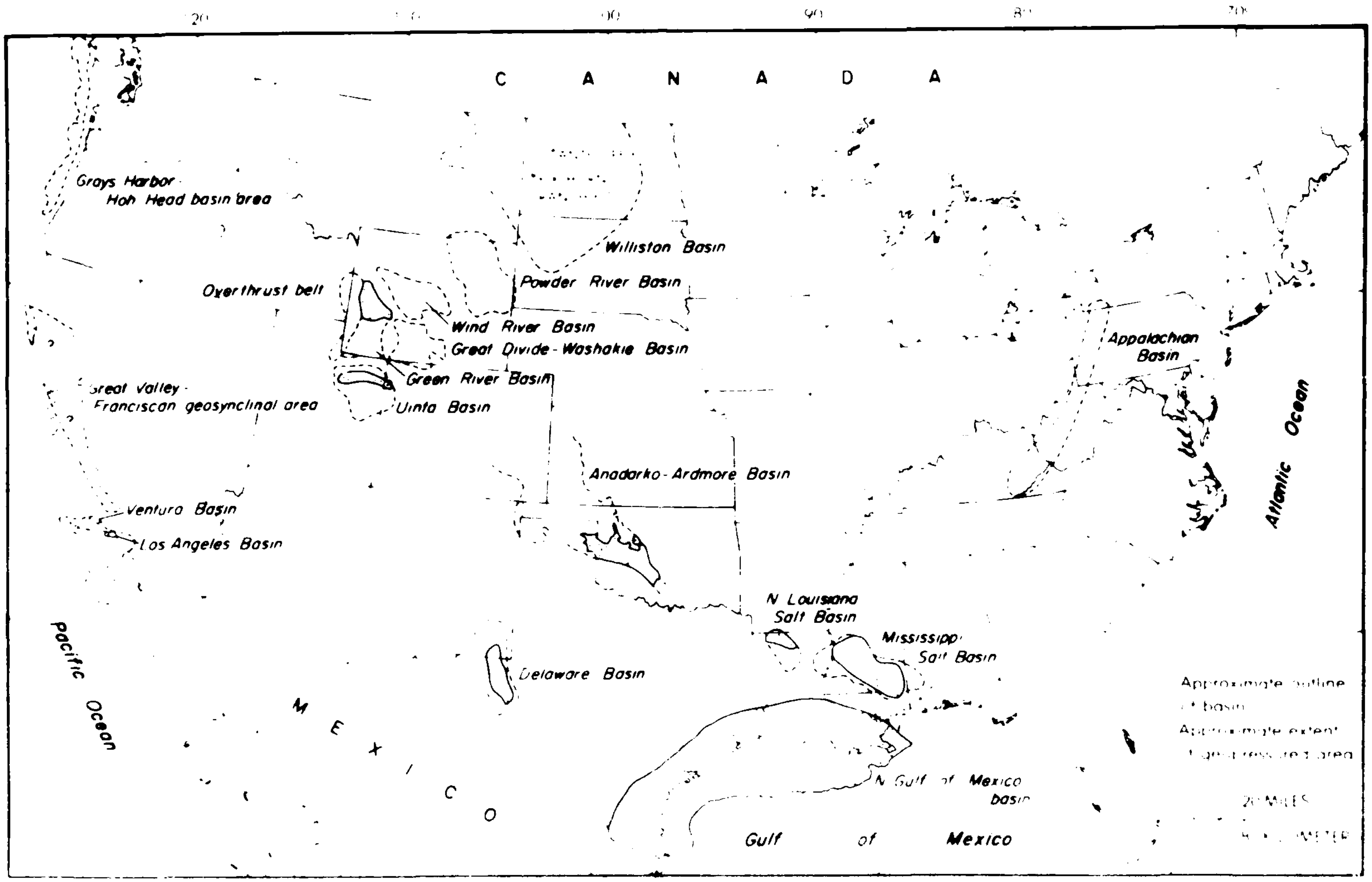
Geopressured Geothermal Reservoirs

Geopressured zones have been identified in stratigraphic horizons underlying the Gulf Coast region. Here, impermeable shale overlies and underlies porous and permeable sandstone beds that contain hot water and dissolved methane gas under abnormally high pressures. Compaction and compression of these sands and their contained water during deposition has caused them to be confined under pressures that are well above normal hydrostatic values for their depth: as much as 10,000-15,000 psi at depths of 5,000-20,000 ft (2-6 km). These abnormally high pressures are the key mechanisms for making it appear economically attractive to bring to the surface water that ranges in temperature from 212-555°F (100-291°C). Extraction of the dissolved methane gas and the potential to develop useful hydraulic energy from the water pressure "head" at the well offer additional economic incentive.

Hydrogeologic conditions similar to those encountered in the northern Gulf Coast region have been identified in other sedimentary basins, suggesting that geopressured-geothermal energy may be developed in these areas. Figure 2 shows the location of these basins in the U.S.

Normal Gradient Geothermal Reservoirs

Where the earth's crust has not been seriously deformed by mountain building or volcanic action, its temperature increases at a fairly constant rate with depth. This rate of increase is the geothermal gradient, obtained by dividing the difference between the temperature obtained


CANADA
Grays Harbor-Hoh Head basin area
Overthrust belt
Williston Basin
Powder River Basin
Wind River Basin
Great Divide-Washakie Basin
Green River Basin
Uinta Basin
Great Valley-Franciscan geosynclinal area
Ventura Basin
Los Angeles Basin
Anadarko-Ardmore Basin
Appalachian Basin
Atlantic Ocean
Pacific Ocean
MEXICO
Delaware Basin
N Louisiana Salt Basin
Mississippi Salt Basin
N Gulf of Mexico basin
Gulf of Mexico

underground and the mean annual surface temperature by the depth where it was measured.

"Normal" temperature gradients are not well defined in geothermal literature. This may be due to the more intense interest focused by authors and investigators on abnormal situations. There is also some inconsistency when it cannot be determined whether mean annual surface temperatures have been considered in calculating a geothermal gradient.

Oil field experience in sedimentary basins suggests that while the temperature gradient is generally constant within any one hole, it may vary greatly from area to area, even in the same stratigraphic sequence of rocks. The geothermal gradient in a sedimentary basin has been found to average 2°F/100 ft (30.6°C/km) [Levorsen (1967)]. In regions of sedimentary rocks, a well drilled to 10,000 ft with a normal geothermal gradient of 2°F/100 ft would be expected to encounter fluid temperatures of 260°F (127°C) (a surface temperature of 60°F plus the average 2°F/100 ft average gradient). It is not uncommon to encounter "normal" gradients ranging from less than 1.4°F/100 ft (19.6°C/km) to more than 2.6°F/100 ft (41.3°C/km) described in geothermal literature.

In some areas where thick accumulations of geologically recent, water saturated, relatively unconsolidated sands and gravels are present, or where oil well drilling data suggest consolidated porous and permeable sediments at depth, significant geothermal resources may be developed. The limiting factors in addition to temperature and depth are the volumes of water that can be produced, the hydrostatic head (must it be pumped?), possible treatment of scaling and corrosion problems, and requirements for disposal of "used" water. If these are deemed economically acceptable, there is no reason to avoid geothermal exploration programs in areas of "normal" gradients.

It is not uncommon to encounter temperatures exceeding 200°F (93°C) in oil field waters. In older, established fields the volume of hot water produced may greatly exceed that of the oil. This hydrothermal resource, made available as an inexpensive by-product of oil production, is currently being examined for direct heat applications by communities and industries with access to it.

Air

Receiving little attention in consideration of geothermal resources, to the extent that many investigators ignore it entirely, is air. The use of subsurface volumes of air to heat or cool enclosed areas on the surface should be considered an important part of geothermal resource analysis. Ventilation of deep mines for removal of gases and heat is mandatory in all mining areas and offers the potential for use of wasted heat in mine operations or mine-mouth industrial applications. Many have observed the constant, generally cool air temperatures associated with large caverns, which is sometimes used in contiguous commercial operations for space cooling. In areas

overlying large, thick deposits of relatively unconso[illegible] alluvium and porous and permeable rocks above a water table, it may be possible to inexpensively extract large volumes of cool or warm air of constant temperature to reduce dependence on conventional energy sources for space heating or cooling.

Quantification of Geothermal Resources

The USGS [Muffler (1979)] indicates that hydrothermal convection with temperatures greater than 302°F (150°C) already identified in western states are capable of developing 21,000 megawatts (MW) of electrical generating capacity. These, in addition to the 1,[illegible] MW available at the unique dry steam, vapor-dominated regime at The Geysers would be equivalent to about 4.25 percent of the country's 532,[illegible] MW of existing electrical generating capacity if they could be fully developed. Table 2 shows the current and planned geothermal electrical generating capacity in the world, by country.

However, when the entire volume of rock in the U.S. is examined, a geothermal resource base is established that is staggering in its implications. The USGS suggests that more than 33,000,000 quads (1 quad = 10^{15} = 1,000,000,000,000,000 Btu's or the energy contained in about 1 billion mcf of natural gas) of thermal energy is contained in the earth's crust to depths of 10 km (32,800 ft or 6.2 miles). The magnitude of this potential resource becomes readily apparent when it is compared with the approximately 75-78 quads of energy consumed in the U.S. each year. Table 3 shows the relative values assigned by the USGS to the nation's geothermal resources.

Of course, being a resource does not make this enormous potential energy supply available as a usable reserve. Perhaps a more realistic goal is converting the estimated 3,300,000 quads of geothermal energy the USGS report implies exists at depths of less than 10,000 ft (3 km) to a viable reserve.

Another source evaluating geothermal resources is the Electric Power Research Institute (EPRI). In a recent analysis, EPRI (1980) suggests that, excluding normal gradient heat which is defined as 77°F (25°C) per kilometer (about 2.35°F/100 ft), the total accessible enthalpy (heat content) in petrothermal (hot dry rock), geopressured, and hydrothermal reservoirs at temperatures above 59°F (150°C) to a depth of 6.2 mi (10 km) is 1.2 million quadrillion (1.2×10^{21}) Btu, or more than a 15,000 year supply of energy at current U.S. consumption rates.

Of this enormous potential resource base, the hot dry rock regime (conductive systems) accounts for some 85 percent of the total, none of which, according to EPRI, can now be counted as recoverable for electric power production.

Geopressured zones of the Gulf Coast make up another 14 percent, with about 165,000 quadrillion (165×10^{18}) Btu. The major concern over geopressured resources today is whether they are sufficiently concentrated to be economically attractive. Evaluation of this resource potential is being developed in a $39 million DOE program [IGCC [illegible]

Hydrothermal convection systems are the major focus of today's electric power research and development efforts by EPRI, DOE, private energy companies and utilities even though they represent barely 1 percent of the total geothermal resource base. Of about 9,600 quadrillion (9.6×10^{18}) Btu, the anticipated recoverable portion is about 2,400 quadrillion (2.4×10^{18}) Btu, with about 900 quads ($900 \times 10^{1[illegible]}$ [illegible]

Table 2. Worldwide geothermal electricity generation (to 1984) [Interagency Geothermal Coordinating Council (1980); Electric Power Research Institute (1980)]

Country	Present Capacity (MWe)	Planned Expansion (MWe)
China	4.5	-----
El Salvador	60.0	385.0
Iceland	64.0	-----
Indonesia	0.3	-----
Italy	420.6	400.0
Japan	168.0	250.0
Kenya	-----	35.0
Mexico	153.0	140.0
New Zealand	202.6	150.0
Philippines	224.2	1,105.0
Taiwan	0.3	-----
Turkey	0.5	14.0
USSR	5.0	58.0
United States	800.0	1,401.0
TOTAL	2,103.0	3,938.0

	Accessible resource base to 10 km (10^{18} J)	Accessible resource base to 7 km (10^{18} J)	Accessible fluid resource base to 6.86 km (10^{18} J)			Accessible resource base to 3 km (10^{18} J)			Resource (10^{18} J)	Electricity (MWe for 30 yr)	Beneficial heat (10^{18} J)
			Sandstone	Shale	Total	>150°C	90°–150°C	Total			
Conduction-dominated											
Land area	33,000,000[a]	17,000,000[b]	—	—	—	—	—	3,300,000[a]	—	—	—
Offshore Gulf Coast	370,000[c]	180,000[c]	—	—	—	—	—	36,000[c]	—	—	—
Total	**33,000,000**	**17,200,000**	—	—	—	—	—	**3,300,000**	—	—	—
Igneous-related											
Evaluated	101,000	—	—	—	—	—	—	—	—	—	—
Unevaluated	>900,000	—	—	—	—	—	—	—	—	—	—
Total	**>1,000,000**	—	—	—	—	—	—	—	—	—	—
Reservoirs of hydrothermal convection systems (≥90°C)											
Identified	—	—	—	—	—	950[d]	700	1650[d]	400	23,000	42
Undiscovered	—	—	—	—	—	2800-4900	3100-5200	8000	2000	72,000-127,000	184-310
Total	—	—	—	—	—	**3800-5800**	**3800-5900**	**9600**	**2400**	**95,000-150,000**	**230-350**
Northern Gulf of Mexico basin (onshore and offshore)											
Thermal energy	850,000[e]	410,000[e]	11,000	96,000	107,000	—	—	—	270[f]–2800[g]	—	—
Methane energy	—	—	6,000	57,000	63,000	—	—	—	158[f]–1640[g]	—	—
Total	—	—	**17,000**	**153,000**	**170,000**	—	—	—	**430[f]–4400[g]**	—	—
Other geopressured basins	—	—	—	—	**46,000[h]**	—	—	—	—	—	—

Table 3. Geothermal resources of the United States. Note: This table illustrates enormous potential for geothermal resources (footnotes on table refer to qualifiers used by investigators. Refer to USGS Circular 790, p. 157 for details). 10^{18} J (Joules) = 10^{15} Btu (British Thermal Units) = 1 quad of energy. Consider that the U.S. consumes about 75 Quads of energy a year and you gain an impression of the magnitude of a resource base that exceeds 33 million quads! Another rough equivalency is that one quad converts to the energy contained in 1978 million barrels of oil or, 55.6 million tons of western coal or, 980 million mcf of natural gas or, 15.6 million pounds of uranium [illegible] (1979)].

above the 302°F (150°C) threshold useful for electricity production with present technology. "Dry" steam systems like The Geysers contain only 40 quadrillion (40 x 10^{15}) Btu, about a quarter of which is represented by the 2,000 MW of capacity already in place or planned for this unique field. According to EPRI, the known hydrothermal reservoirs that contain about 220 x 10^{15} Btu (220 quads) in recoverable steam and hot water translate to 24 gigawatts (24 GW or 24,000 MW) of generating capacity with a life of at least 30 years. Other inferred prospects at temperatures above 150°C (302°F) extend the potential by another 96 GW.

EXPLORATION PROCEDURES FOR VERIFYING GEOTHERMAL RESOURCES

Overview

The earth's high internal temperature means that useful heat underlies every part of it. In order to be economically recovered, however, this heat must be found in concentrations that can be reached by drilling and with features that permit it to be brought to the surface. Water is the medium by which the earth's thermal energy is moved from a deep igneous primary heat source to a reservoir accessible to the drill, as well as the means of transferring the host rock's heat to the surface. Porosity must be present or the rock will contain no water and permeability is required to move the water into a well borehole. These natural properties -- concentrated heat, water, porosity and permeability -- need to be quantified in an exploration program to discover geothermal reserves. If these properties are not all present (or cannot be induced through, for instance, hot dry rock systems, mechanical rock fracturing, etc.), a usable geothermal resource will not be present.

Most mineral commodities have an economic cut-off "grade" that is usually a function of the concentration by volume and percent of the ore and the cost required to recover it. The analogy to geothermal resources is in relating volume to size and extent of the reservoir and its ability to give up fluids, and percent to temperature. An evaluation of applying human and financial resources to an exploration program that must drill a deep well in a remote area for an anticipated extensive reservoir with rocks capable of giving up large volumes of fluid at temperatures in excess of 500°F (260°C) is considerably different than for a reservoir of limited extent, low producibility and low temperature. In contrast to mineral resources, however, the economic cut-off "grade" for a geothermal resource is also a function of use. If electricity generation is the goal of a geothermal program, "high grade" resources are a necessity. If, on the other hand, direct heat applications are a major consideration, "lower grade" geothermal resources may warrant an exploration program.

As with oil and gas exploration, depth is a limiting factor in geothermal exploration and development within a practical and technological range. The current world drilling depth record is 31,441 ft established by Lone Star Gas Co. in Beckham Co., Oklahoma, in 1974 [Oil and Gas Journal, Vol. 75, No. 35, August 1977]. Technology exists to drill a deeper well but there is presently no economic incentive to do so.

Realistically, and true of any energy resource including geothermal, the economic limits are basically those of Btu's: if there are enough of them, it matters little what form they are in if they are recoverable in a socially and environmentally approved manner to be beneficially

applied at a cost acceptable to the user. Fulfilling these qualifica-tions is the purpose of a geothermal exploration/verification program.

Any analysis leading to a decision of either to verify a geothermal resource by drilling an exploratory well or to abandon the project must be the result of combining the efforts, knowledge and expertise of a number of disciplines. Every geothermal reservoir will be somewhat unique and different from all the others. Its occurrence may be the end result of numerous physical variables, only a few of which can be determined in advance of drilling the well.

Exploration for a geothermal resource and coordinating and directing the efforts of others involved in the process of developing the data upon which the drilling decision is made is the province of the geologist. The location of the initial well, the rationale for drilling it, the depth to which it should be drilled, and the parameters of the antici-pated reservoir are all geologic problems. Depending on the variables involved, it may be necessary only to assess a simple combination of structure, petrology and hot springs. Or, it may require taking into account a large array of information involving the various specialties of structural geology and tectonism, petrology, petrography, sedimenta-tion, stratigraphy, geologic history, metamorphism, fluid hydraulics, hydrology, geophysics and geochemistry. Other professionals in related sciences, such as physics, chemistry, biology, and engineering may be called upon to contribute pieces to resolving the geological puzzle.

The geologist(s) must assemble all the data on the area and assess it for relevancy and accuracy. They must compile the geology from what is visible and can be mapped at the surface, and from all available well and geophysical data for depths ranging to 6 miles (10 km) below the surface. The assumptions, predictions and conclusions are almost invariably going to be based on incomplete and fragmentary data, much of which are obtained from experts without a working knowledge of geology or from geologists who may have worked previously in the area with no interest in the geothermal possibilities. All of this information must be carefully assembled, interpreted with the benefit of mature judgment and related experience, described with maps, cross sections and text that are refined to indicate the most favorable place to drill a well and clearly and logically presented to those responsible for the commit-ment to drill. Although the geological recommendation may be highly favorable to encounter a geothermal reservoir, it should be clear that there is no known method to confirm its existence until a discovery well is drilled.

The geothermal resource must be discovered before it can be of any use to society. This means wells must be drilled. It is interesting to note that despite expenditures of $570 million for geothermal by the Federal Government in fiscal years 1977-1980 (Table 4), and addi-tional millions by private industry, an insignificant number of geo-thermal wells have been drilled. An average of only 55 per year were drilled in 1975-78. In 1979, 80 wells were completed. California's Imperial Valley and The Geysers account for 65-75 percent of all geo-thermal drilling in the U.S., suggesting that very few exploratory wells are being drilled outside of proven reservoirs where economic feasibility has already been demonstrated. No more than 19 major wells were drilled beyond this region in any year through 1978 [ICF (1980)]. Compare this with the 59,107 wells projected to be drilled in the U.S. by the oil industry in 1980, 12,376 of which are exploratory "wildcat" wells [Oil and Gas Journal, July 28, 1980].

Table 4. Federal funding for geothermal energy (in $ thousands)
[Interagency Geothermal Coordinating Council (1980)]

Organization Unit	Actual FY-77	Actual FY-78	Actual FY-79	Estimated FY-80	Requested FY-81
Department of Agriculture					
U. S. Forest Service	40	678	775	750	739
Department of Defense					
Navy	758	542	924	17,100	17,800
Air Force	15	0	13	21	2,400
DOD Total	773	542	937	17,121	20,200
Department of Energy					
Energy Technology	53,326	105,962	142,637	138,428	142,000
Resource Applications			9,737	9,026	10,000
Office of Energy Research	1,900	2,800	3,200	3,400	4,000
Environment	3,862	3,896	3,167	2,303	2,949
Geothermal Loan Guaranty Fund (Administrative Expenses)	380	410	189	1,180	1,091
DOE Total	58,468	113,068	158,930	154,534	160,040
Department of Interior					
Fish and Wildlife	200	200	200	74	74
Bureau of Land Management	2,500	2,300	2,585	2,600	2,600
Bureau of Mines	528	550	1,050	800	400
Water and Power Research Service	2,557	1,800	555	910	60
Geological Survey, Geothermal Research Program	9,384	10,184	12,043	10,092	7,569
Geological Survey, Geothermal Evaluation and Lease Regulation	1,512	1,854	2,194	1,994	1,994
DOI Total	16,681	16,888	18,627	16,470	14,423
Environmental Protection Agency	600	670	750	750	750
National Science Foundation	200	175	70	0	0
Total Federal Geothermal Program Budget	76,782	132,021	180,089	189,696	196,152

The petroleum and mineral industries, through years of [illegible] practice, have developed successful exploration techniques th[illegible] transferred to the search for geothermal resources, especially [illegible] regimes in the low to moderate temperature range. There is [illegible] dence, however, of reluctance on the part of geothermal inv[illegible] to readily accept strategies developed by others in favor [illegible] research on their own methods [Ball, et al., (1979)]. This [illegible] result of government assistance programs assigning high [illegible] research investigations of high temperature geothermal re[illegible] electrical generating capacity as well as the narrow focus of [illegible] energy companies on these economically attractive systems. [illegible] the exposure of society to effective fuel and cost benefits [illegible] moderate temperature direct geothermal applications has unne[illegible] lagged.

Particularly with respect to high temperature hydrothermal [illegible] should be recognized that virtually all the reservoirs that h[illegible] or are being developed do not owe their discovery to science. [illegible] simply located on or near obvious surface manifestations su[illegible] springs, geysers and youthful volcanic centers. The process [illegible]-covery is similar to that of the petroleum and mineral indus[illegible] almost a century ago when most of the high grade ore deposits [illegible] carbon seeps in the U.S. were found by casual observation follo[illegible] primitive, but often effective, exploration techniques relat[illegible] face exposures.

Obviously, geothermal exploration and reservoir definition use[illegible] sophisticated mechanical and deductive processes than were [illegible] early mineral and fuel prospectors. Yet, there is still a tend[illegible] concentrate exploration techniques on parameters that are measur[illegible] near the surface. It is likely that just as petroleum and minera[illegible] exploration has advanced far beyond this phase of reservoir det[illegible] geothermal techniques will begin to focus on the deeper, isolat[illegible] fined reservoirs that will have little or no definitive surface [illegible] of their existence. This will be especially true as greater eff[illegible] placed on the discovery and development of usable regimes wit[illegible] tures lower than those required for electricity generation. [illegible] exploration will not be limited to areas of heat escape or ab[illegible] high temperature gradients. The processes of geological deduction, analogy and prediction, supported by geophysical and geochemical [illegible] will define the useful geothermal reserves of the future as they [illegible] revealed society's other raw materials in the past.

Preliminary Assessments, Data Sources

A great deal of useful, nonproprietary information regarding [illegible] resources ranging from broad, all-inclusive regional overviews t[illegible] specific analysis is available today from a number of sources. [illegible] themselves of these may provide those responsible for evalu[illegible] thermal options on Air Force bases a rationale for developing [illegible] It is important to recognize that divergent opinions regardin[illegible] specific resource assessments are not uncommon at this prelim[illegible] "conversational" level, even among professionals sharing simil[illegible] disciplines.

At this stage, some of the information that can be obtained [illegible] published maps and documents, state of knowledge about geotherm[illegible] systems in the area, and identification of persons who may be fa[illegible] with the area's geothermal resource potential. Determining that definitive data are lacking does not necessarily mean that th[illegible] thermal potential is negative. It usually means only that it [illegible] been investigated. Appendix A lists geothermal data sources.

Although not strictly resource verification procedures, there are other important matters that should be addressed as part of a preliminary assessment of the geothermal potential. One is establishing the status of ownership of the mineral estate. Where Air Force installations have been developed on lands acquired by the Federal Government from private owners through purchase, condemnation, donation, etc., title should be searched to determine whether the mineral rights were obtained in the transfer of ownership. The question of ownership, acquisition or availability of water rights and the disposal of geothermal fluids is another potential problem area which may involve the authority of the state. Important legal and institutional questions that uniquely apply to resource development on Air Force installations are addressed by Austin and Whelan (1978).

Geological Verification Methods

General Considerations -- Geothermal reservoirs in the high temperature hydrothermal regimes have been encountered in a large variety of rock types. Major production in New Zealand's Wairakei field is from acidic volcanic rocks, as is the production in geothermal areas in Japan. At Larderello, Italy, production is from fractured limestone and dolomite. The host rock at The Geysers is fractured greywacke. Ancient river delta sediments are the zones exploited in northwest Mexico's Cerro Prieto field and southcentral California's Imperial Valley area [Banwell (1970)]. The Baca field in New Mexico's Jemez Mountains will produce from porous and fractured welded to non-welded rhyolite ash flows and pumice [Union Oil Co., et al. (1978)]. At the Roosevelt Hot Springs geothermal site in Utah, the reservoir has been described as Tertiary igneous intrusive granitics of Precambrian metamorphics, capped by altered and cemented alluvium. The Roosevelt reservoir is characterized by having virtually no intergranular porosity and permeability, so production will be fracture controlled [Green and Wagstaff (1979)]. This diversity of occurrences makes it difficult to focus geological exploration for geothermal resources on uniform parameters common to most reservoirs.

Generally, the high temperature resources described above were not scientific discoveries and their selection for development is predominantly a function of obvious surface evidence. Geology and geophysics in these areas are primarily development techniques being applied to gain knowledge of reservoir conditions, the aerial extent and geometry of the field, and siting of production and step-out wells. These data will certainly be useful when applied to cost saving efforts to exploit similar reservoirs. However, outside of establishing the diversity of rock types that may contain hydrothermal reserves and the conditions under which they may give up their heat, definitive data relating to successful exploration techniques, especially in regions where abnormally high thermal values are not evident on the surface, are lacking.

Evidence to date indicates that usable geothermal resources are associated with one or more of the following geological features.

1) Young volcanices -- Not all volcanoes erupt the same kinds of materials. Investigators suggest that volcanic centers characterized by basic igneous rocks such as basalt and andesite may not be as prospective for geothermal regimes as those associated with silicic magmas like dacite and rhyolite [White and Williams (1975)]. The rationale is that basalts and andesites, which form most of the world's volcanoes, have probably risen very rapidly from the earth's mantle to the

surface through narrow vents. As a result their heat is dispersed rather than stored so that, with the exception of the large oceanic volcanoes and eruptions that have taken place within the past few thousands of years, they rarely form thermal anomalies of economic interest. On the other hand, the high-silica varieties have very high viscosities, and are commonly derived from extensive magma chambers located at relatively shallow depths within the earth's crust. These igneous intrusions can sustain large heat systems for thousands of years.

Many published geologic maps have sufficient detail to distinguish between basic and silicic igneous rocks. Radiometric age-dating of igneous rocks is an invaluable aid to geothermal exploration which is becoming more reliable and widespread in its application.

2) <u>Regions of relatively recent tectonism</u> -- Tectonic movement is associated with faulting. Faults are considered primary conduits for convection in hydrothermal systems, and fracture systems associated with faulting may be the geothermal regime's primary porosity. Regions of active mountain building, tilting, foundering and rifting of crustal blocks are good candidates for encountering economically useful geothermal reservoirs.

3) <u>Hot springs, geysers and fumaroles</u> -- Most areas of active expulsion of hot water and steam on the surface have been identified and their geothermal potential assessed. Strong surface activity of this type is geologically short lived and ephemeral and probably represents only a minor phase of a much more extensive period of host rock heating and cooling. Rapid changes in thermal activity are one of the most outstanding characteristics observed at Mammoth Hot Springs in Yellowstone National Park. Here, hot spring activity resulting in deposition of travertine apparently began about 63,000 years ago, although these early hot water sources have been inactive for thousands of years that predate the latest glacial episode. Hot springs in the Mammoth area are now confined to local discharges that apparently began 3,000 to 4,000 years ago [Barger (197[illegible])].

A key to future exploration may be in searching for inactive hot springs. It would appear that a great deal of useful heat would continue to be stored in a host rock and associated aquifers long after surface manifestations have disappeared. Natural conditions such as climatic changes can upset the equilibrium of a cyclic convection system, with arid conditions drying up the source of meteoric (rain) water supplying the spring and greater rainfall masking the thermal effect with an oversupply of cold water. Earthquakes and landslides may terminate a spring. Precipitation of minerals contained in hot water solutions can seal a spring's natural conduit. Although inactive thermal spring areas are not by themselves indicative of near surface useful heat, their discovery warrants further investigation.

Analysis of thermal water deposits may be a useful exploration tool. Experience indicates that water with solutions high in silica result in siliceous sinter deposits of quartz, opaline and cristobalite around geysers and hot springs where temperatures exceed 356°F (180°C). Extensive travertine deposits result from precipitation of calcium carbonate ($CaCO_3$) from solution where reservoir waters have lower temperatures [White in Krueger and Otte (1973)].

4) Deep sedimentary or alluvial basins -- Usable thermal values are common in deep basins. A tectonic basin with a thick suite of sedimentary rocks will amost invariably have been tested by the drill for its oil and gas potential. Analysis of the geothermal gradient determined by bottomhole temperature measurements in wells drilled for other purposes will yield valuable information about heat sources and the site of potential thermal regimes [Chaturvedi and Lory (1980)]. Examination of well samples, cores, electrical and mechanical logs, drill stem tests and production data can establish the porosity, permeability, and productivity factors of various units.

Thick, water saturated alluvial deposits such as those identified in valleys in the Rio Grande Rift and Basin and Range Province are associated with recent tectonism and, in some areas, late volcanism. Whether a result of these phenomena or a normal increase of temperature with depth, hot water is not uncommon. If the aquifer is unconfined and the water table is close to the surface, or a confined aquifer has sufficient hydrostatic pressure to move hot water to or near the surface, reducing pumping costs, these provinces offer considerable promise for direct heat applications where they occur near populated centers.

5) General assumptions -- Usable hydrothermal systems originate from a hot intrusive igneous or anomalously radiogenic source rock from which significant thermal values are conveyed by conduction to an overlying ground water regime. With interconnection between surface recharge areas and the heat source, cyclic convection systems are formed and buoyant hot water will rise to the surface where it is expelled in geysers and hot springs. If there is no path to the surface the hot water may be confined in the aquifer between insulating rock layers with low thermal conductivities. If an anomalous temperature regime is established it will be superimposed on the sedimentary, igneous, or metamorphic rock units that host the water. The primary difference between a natural hydrothermal system and a hot igneous conduction system (hot dry rock) is that the water and permeability must be artificially introduced to the host rock by mechanical means in the latter regime.

6) Exceptions -- For virtually every assumption regarding mechanisms controlling geothermal reservoirs, there will be exceptions. Almost every geothermal system will have features that are unique from all the rest and combinations of two or more mechanisms to form a usable system may be common.

The Klamath Falls, Oregon, geothermal system is an example of how a combination of geologic factors result in a unique reservoir that, despite 50 years of use and study, is still not completely understood. In this vicinity there are at least 7 thermal artesian springs and 800 thermal wells, more than 400 of which are used in the most extensive direct heat, nonelectric applications in the U.S. The region is one of extensive recent volcanism that culminated in the cataclysmic eruption of Mount Mazama (Crater Lake) some 50 miles north about 6,700 years ago. The rocks are of basaltic composition with little likelihood of containing high temperatures at depths shallow enough to be reached by circulating ground water. Silicic volcanics, which would be expected nearby in order to account for Klamath Falls' thermal anomalies, have not been found. In the absence of parameters that should be present, it is necessary to perceive a system that relies predominantly on the earth's normal thermal gradient to produce the heat, with circulation of ground water to great depths. Permeable channels through faults bounding the Klamath Falls graben must extend to depths of 15,000 ft in order to attain the system's 302°F (150°C) temperatures, unless aquifer temperatures at shallower depths are elevated both by convective transport and by the blanketing, insulating effect of rocks of low thermal conductivity overlying the reservoir [Sammel (1980)].

Literature Search -- One of the first steps in assessing geothermal potential is obtaining access to all relevant published and unpublished information on the geology, hydrology, geophysics and geochemistry of the area of interest. Those sources considered most likely to have useful information include state and federal energy and geological agencies; university libraries, earth science departments, and research institutes; federal and state supported public and private energy research and development laboratories, companies, and organizations; scientific and professional publications; and professionals in private practice. Published information consists of maps and publications that can usually be found in library indexes or indexes by subject, location or author of the various entities producing them. Some entities such as USGS, the National Aeronautics and Space Administration's (NASA) Technology Application Center (TAC), and various research firms can retrieve geological/geothermal information, for a fee, from a number of computer data bases such as NASA, DOE, NTIS, WATSTORE, GEOREF, and TULSA. All public agencies may have pertinent subject data in the form of unpublished information available as inter-office memos, open-file reports, and theses.

It is a time consuming but necessary task to locate data and assemble, read, review, analyze, and evaluate it. Generally, a geologist with some professional familiarity with the area can accomplish this objective more rapidly and thoroughly than one without experience in the region.

The purpose of the literature search is basically to determine whether existing information is positive, negative, or neutral with regard to ... ric conditions that may control a potential geothermal system. ...ation of tectonic conditions, volcanic activity, rock types and thicknesses, geothermal gradients from well logs, hydrodynamic conditions including water tables and springs, geophysical data, and geochemical information are a necessary prerequisite to determine whether additional investigations should be undertaken. This assessment can point out where important data are missing, it may prevent duplication of information if additional programs are initiated, and it should be of value in interpretation of new data obtained from an exploration ...ure.

If published geothermal information is available, it is unlikely to be site-specific for the area of interest except in the broadest terms. Existing geologic information was probably developed for purposes other than geothermal analysis and must be evaluated and interpreted with the knowledge that it is likely to be incomplete and inconclusive.

Information should be examined in the context of identifying whether one or more of the characteristics of geothermal systems previously discussed ... apparent or likely to occur. Evidence may be extensive and conclusive that there is little or no opportunity for discovering and developing a usable geothermal regime because the controlling geological parameters do not exist or it is not economically feasible to verify them. Since geothermal resources are often examined for a specific application, careful consideration should be directed to whether a reservoir that is inadequate for one purpose may be suited for another. If, for instance, the assessment is negative for regimes necessary for electricity generation, are there lower temperatures that may be developed for space heating?

If the evaluation reached by the literature search verification phase is negative, a geothermal exploration program may not be recommended. It is more likely, however, that evidence will be inconclusive and additional steps may be warranted to resolve unanswered questions.

Aerial Photography -- Modern aerial photography is an excellent tool to quickly and relatively inexpensively evaluate the surface structure and ...tigraphy of large and small areas. Geological mapping can be accomplished directly on aerial photos in many regions.

Aerial photographs of much of the United States are available from public sources at minimal cost. Most topographic maps are constructed from aerial photographs taken for the USGS. In western states the U.S. Forest Service, Soil Conservation Service, Bureau of Indian Affairs, and Bureau of Land Management often have photo coverage in color and black and white, at suitable scales from low level detail ...:6,000 to high altitude regional at 1:40-60,000. Overlapping images ... usually available which, when examined with stereoscopic magnifying ...ses, afford the viewer a 3-dimensional perspective of the surface features.

Landsat imagery is a spinoff of space age technology that offers geologists an immediate regional view of the geology of almost any area on earth. Landsat does not use photographic cameras to take conventional pictures from its 570 mile high orbit. Instead, a multispectral scanning device uses an oscillating mirror that scans the earth and a telescope that focuses visible and near infrared light waves reflected from the earth into the satellite's radiation detectors, which measure ... light intensities in 1.9 acre resolution picture elements, or

"pixels," in four different spectral bands. These values are converted into computer-digestible numbers, from 0 to 63, and transmitted back to earth at the rate of 15 million per second. Through an electronic recorder, this stream of data becomes imagery on photographic film at a scale of exactly 1:250,000, with each "photograph" covering 115 miles on a side or 13,225 square miles of area. Because images are computer produced they can appear in color or black and white, as well as a multitude of specialized, computer "enhanced" renditions that emphasize specific features. These images are particularly useful in geothermal exploration in identifying prominent linear elements representing fault zones, shear zones, basin margins, uplights, mineralized or hydrothermally altered areas and other features that are not readily apparent in a larger scale photo or on the ground. A black and white copy of a small part of an enhanced color landsat image, showing Albuquerque and Kirtland Air Force Base, New Mexico, is illustrated in the frontispiece.

Other specialized photography utilizing remote sensing equipment and side-scanning radar is useful in detecting fault lineaments in areas where dense ground cover or clouds conceal the earth. These photo techniques are not as readily available as conventional photography and may be comparatively expensive to acquire.

Infrared photography is another specialized technique that may be of limited use in identifying surface "hot-spots." It is probable, however, that any area with temperature anomalies of the magnitude to be discerned on photographs will have already been identified by other observations. Banwell (1970) describes the successful use of daylight color infrared film to identify patterns of thermally altered ground in areas of extinct hot springs that had not been previously mapped.

Aerial photos give little direct information on subsurface conditions relating to structure, stratigraphy and the distribution and configuration of possible geothermal reservoirs. Used in combination with other data, including field investigations, however, they become one of several methods used by the geologist to extrapolate and predict subsurface conditions.

Field Investigations -- Field investigations are basically of two types: relatively brief reconnaissance ventures designed primarily to check and verify geologic data obtained from the literature search, other sources, and "in-office" interpretation of aerial photos; and longer lasting detailed programs that will produce original geology in areas where there is no useful information or where an intensive, focused effort is appropriate in order to refine a prospective geothermal anomaly to a drilling recommendation. It is usual for a reconnaissance effort to precede a detailed study. In rare instances where the geology of the area of interest has been thoroughly and competently mapped, even if for purposes other than verifying the geothermal potential, it may be possible to adapt this data to the geothermal exploration program with a minimum of additional field work.

Unless there is a specific geothermal target previously identified, the reconnaissance investigation starts with defining the regional geologic patterns and determining whether any of the characteristics of geothermal systems are present. In some ways the methodology may be likened to a process of elimination in order to narrow the search to those local areas within the region that are the most likely candidates for detailed examination. Even in a situation involving a site-specific analysis of lands owned or controlled by the entity responsible for the exploration program, the broader aspects of the region's geology must be considered and related to the smaller area.

Field investigations can incorporate many procedures that depend upon the objectives of the analysis and the kinds of terrain involved. Excursions may involve the use of conventional vehicles, off-road equipment, airplanes, helicopters, boats, horses and hiking shoes. Quite often, USGS topographic maps of a suitable scale and standard or enlarged aerial photos are used as a base to directly plot geologic data observed in the field. Pertinent, relevant and significant geology derived from the literature search, other sources and photo analysis may be transferred from the original source to the field base map or photo so that it may be easily checked. It is important to the project's conclusions that outside data be verified and their accuracy substantiated by observation. In many instances a previous geologic investigation may have been of a casual, reconnaissance nature adequate for the specific study. A closer examination may result in a different interpretation of data, relocation of features, and discovery of additional evidence that may have been overlooked by other investigators. The field investigation phase includes obtaining samples of rocks and water samples from springs, wells, lakes and streams. These can be analyzed for definitive constituents by commercial laboratories if in-house facilities are not available.

If geothermal prospects are identified or suspected, the reconnaissance investigations may evolve into more detailed studies involving precise geologic surface mapping and surface mapping and acquisition of other supportive data. At this point it may be convenient for the geologist to summarize the results of the investigation, incorporating an evaluation of all the pre-existing information as well as those data acquired in the course of the investigation. Since the objective of the geothermal exploration program is to define a drillable prospect by predicting the geologic and hydrologic conditions anticipated in the subsurface, a realistic model should be described. If relatively more expensive procedures such as geophysical surveys, geochemical analysis and temperature gradient wells will help confirm the predicted conditions at depth, they should be described and recommended, and their acquisition approved by the program's responsible parties.

<u>Geophysical Verification Methods</u>

<u>General Considerations</u> -- Geophysical surveys measure variations in the physical properties of rocks beneath the surface. Rocks and the fluids they contain will differ in electrical resistivity, thermal conductivity, density, magnetic influence, and propagation velocity of elastic waves. These parameters are measurable by a number of mechanical means that are collectively called geophysical methods. They are obtained by a variety of instruments set on the surface of the earth, flying over the earth, or placed in wells drilled into the earth. Geophysicists are specialists in the science of the physics of the earth who operate geophysical equipment and interpret the data obtained. Generally, geophysical techniques applied to geothermal exploration involve observing, recording and interpreting the earth's seismic and electrical phenomena, its gravitational and magnetic fields, and the distribution of its thermal qualities. Geophysical procedures in geothermal exploration can be considered to serve two major purposes: as an adjunct to geologic interpretation, and as an aid to the detection and mapping of geothermal reservoirs [Banwell (1970)].

Geophysical measurements, particularly active seismic methods, gravity and magnetic surveys, and some electrical and electromagnetic methods can be extremely useful to refine and quantify the details of underground structural conditions that geological field investigations infer. Often, the use of these instruments and the interpretation of their

data are the only means besides drilling an expensive well to confirm a predictive geological model, substantially modify it, or suggest that its rationale is unsubstantiated.

Presently, active seismic methods, gravity, and magnetic surveys are not widely used in defining a geothermal reservoir, although with additional refinement and interpretive experience there is good potential for their use in delineating hydrothermal zones and determining the location and depth of high temperature source rocks. Their utility is primarily in assisting the geologist to visualize the structural attitudes of sedimentary horizons and their relationships to each other, the surface, and igneous basement; to identify faults and fault zones that may be hydrothermal conduits, together with their orientation; and to determine the thickness of consolidated or unconsolidated sediments, or the depth to basement rocks.

Some geophysical assessments are relatively expensive, and they are often meaningless or inconclusive if not tied to a geological objective. If a geophysical survey is undertaken to support or refine a geological investigation, it is important that the geophysicist understand what it is the geologist is attempting to define and the geologist be aware of the limitations of the geophysical programs considered or selected for the project. Appropriate geophysical procedures can make a substantial contribution to the geothermal target assessment and quality of the geological interpretation. However, before the use of these procedures is recommended, a clear understanding should exist as to what they are supposed to accomplish that other more definitive and, perhaps, less expensive methods cannot.

Geophysical Techniques for Subsurface Resolution -- Active seismic methods require explosives or vibrations to produce shock waves underground. Depending upon the technique selected, the artificial seismic energy is reflected or bounced back to the surface from the interfaces between rocks with different physical properties (reflection method), or the elastic shock waves are refracted horizontally along an interface and then back to the surface (refraction method). The shock waves are generated and measured along a predetermined, spatially located grid system on the ground. Placed on the grid are receivers called geophones that pick up and record signals bounced from the subsurface interfaces. Measuring the velocity and intensity of the signals relative to the source of the elastic wave and the geophones permits the construction of meaningful maps and cross sections of subsurface conditions.

Three methods are commonly used to generate the seismic waves: the explosive method uses a truck mounted rotary rig to drill holes 100-200 ft deep. The holes are loaded with 5-50 pounds of explosives that are detonated (shot) to produce shock waves. The thumping method involves a truck-drawn or self-propelled unit containing a heavy weight or "hammer" which is hoisted and then released to strike the ground to produce underground energy. The vibration method usually requires several trucks operating in unison to apply a vibrating weight to the ground to induce signals.

Gravity surveys are relatively easy and inexpensive field procedures that involve establishing a surveyed grid with good elevation control. Instruments called gravimeters measure variations in the earth's gravitational field. Inclusion of gravity surveys in major geothermal exploration programs in areas of relatively flat topography with poor geological exposures is a particularly effective and rapid reconnaissance tool. Anomalies detected may help define faults, basement structure and relief, and, in volcanic regions, buried calderas, as well as

assist in the location of hydrothermally altered reservoir rocks and igneous intrusives. Unless the geology is very well known, it is likely that gravity anomalies must be refined by more precise and usually more expensive geophysical methods. Gravity surveys may not be cost-effective in mountainous areas of regions with rugged terrain because of the requirement for time-consuming elevation corrections to obtain precise elevation control.

The principle that gravity surveys rely on is that the gravitational field of the earth varies slightly from place to place and that these variations are measurable. Although most of the variation can be attributed to latitude, elevation, and topography, the remainder, called a gravity anomaly (complete Bouguer anomaly), depends principally on the density of local rocks beneath the measurement station. Measurements are made by a complex spring balance called a gravimeter. Anomalies are expressed in units called milligals. The total gravitational field of the entire earth is about one million milligals, but the crustal anomalies of interest in exploration range from about 1 to 100 milligals. Because the gravity anomalies reflect the densities of the rocks underground, it is important to know the densities of the rocks common to the study area. In western states, for instance, rock densities in grams per cubic centimeter range from 2.2 for relatively unconsolidated Quaternary and Tertiary sediments and most volcanics, through 2.4-2.6 for the Mesozoic and Paleozoic sedimentary rocks, to 2.67 for the Precambrian rock types in many areas. Gravity will be high or "positive" where the higher density rocks are near the surface and low or "negative" where the lower density Quaternary and Tertiary sediments and volcanics are very thick. Steep gradients and rapid changes between highs and lows may indicate major fault zones.

<u>Magnetic surveys</u> depend upon similar principles as gravity surveys, except the instruments (magnetometers) detect magnetic intensity variations in the rocks. Although these geophysical procedures have been used in known geothermal fields with some success to detect hydrothermally altered zones where magnetite in the rocks may have been altered to another mineral, and to locate field development wells to intersect faults that control hydrothermal fluid movement, their usefulness as an exploration tool has not been well demonstrated. Under controlled circumstances, aeromagnetic surveys may be a rapid, relatively inexpensive method to map variations in the magnetic field associated with a deep thermal source.

<u>Electrical Resistivity Surveys</u> -- Electrical resistivity surveys, sometimes referred to as electrical and electromagnetic applications, are of three main types: controlled source direct current (DC) methods, controlled source electromagnetic methods, and natural electromagnetic field methods. There are numerous variations within each classification. Electrical procedures have been in use in geothermal exploration for a number of years and have been considered useful primarily to detect a geothermal reservoir and define its spatial limits. However, experimentation with and refinement of a number of these procedures have made some of them equally useful to define faults and depth to basement [Bartel, et al., (1980)], and have limited application to reconnaissance mapping or profiling, vertical soundings, and estimating geologic structure [Ball, et al., (1979)].

Used in geothermal exploration, these techniques measure the ability of rocks at depth to permit natural or induced electrical current to pass through them, or their resistivity. The electrical resistivity of rocks is primarily a function of their temperature, porosity, saturation of the pore space, salinity of the saturating fluid, pore space geometry,

and conductivity of the matrix (clays, etc.). Geothermal reservoirs have higher proportions of these factors collectively than surrounding rocks, so they often register anomalously low resistivities.

Controlled source DC methods, sometimes called DC resistivity profiling, are probably the most common electrical techniques used. The procedure basically involves placing electric current into the ground through two electrodes and measuring the resulting potential difference across another pair (or pairs) of electrodes. Mathematical formulas and theoretical curves are applied by the geophysicist to calculate apparent resistivities of the rocks to arrive at vertical and horizontal spatial relationships that can be mapped and illustrated in several dimensions. The kinds of information obtained depends upon the location of the power transmitter electrodes relative to the current receiving electrodes. The distribution of the electrodes, or grid arrangement, is called an array.

Many varieties of electrode arrays have been employed in geothermal exploration that are derived from two basic systems: centrally symmetrical and acentral. Centrally symmetrical arrays are those whose current and potential electrodes are located equidistant from the center of the array. Instruments used in these configurations normally house the power transmitter and the voltage receiver in the same case, or in two separate cases connected by wire. Examples of centrally symmetrical arrays are the Schlumberger and Wenner. Acentral arrays include the dipole-dipole, gradient, equatorial and azimuthal arrays and their variants. These are normally used in conjunction with resistivity equipment that does not require wire ties between transmitter and receiver.

The selection of an array for field investigation is a function of the maximum probing depth for the particular array, the length of wire required relative to topography and amount of current, equipment limitations and efficiency, cost as determined by the ease of the size of the crew, judgments as to the detail required, and the ease or difficulty of data interpretation. Some arrays like the dipole-dipole are more sensitive than others to lateral changes in resistivity that may be caused by near surface discontinuities in the rocks. These can be used for structural refinements as well as depth soundings and establishing hydrothermal boundaries. The Schlumberger array is convenient to use for depth probing because fewer movements of electrodes are required than with the Wenner array. However, if depth is critical, the Wenner array may prove more effective. The practical limitation of a number of controlled source centrally symmetrical arrays is the length of wire needed to connect the current electrodes, which probably should not exceed about 1 mile (2 km). If resistivity is low, a high current may be required to obtain measurable voltages, so arrays utilizing shorter current electrode spacing may be selected for safety and other considerations. Previous field experience with a variety of arrays in a number of geologic environments can be an important element to a successful geothermal exploration program using controlled source and other electrical resistivity methods.

Natural electromagnetic field methods include telluric, magnetotelluric (MT), and audio-magnetotelluric (AMT) techniques that utilize random electrical and sound signals from natural sources such as thunderstorms and micropulses in the earth's magnetic field to measure resistivity. A principal advantage is that there is no need for a power source. These natural methods are considered to have other advantages over DC methods in geothermal exploration because signal size increases with decreasing resistivity providing for more accurate measurements, and their signals are not adversely affected by near surface high resistivity zones.

Ordinary magnetotelluric devices are sensitive to resistivity measurements at depths ranging from about 2 mi (3 km) to 60 mi (100 km). This feature makes them useful where regional data on deep heat sources in the crust may be of interest. They have limited application in defining a geothermal reservoir, however, because of their relative insensitivity to shallow resistivities.

The audio-magnetotelluric method probes both deep and shallow horizons. Its instrumentation consists of two narrow-band tuned voltmeters that measure the output from a pair of electrodes (dipoles) and a ferrite wound induction coil. By changing frequencies, sets of apparent resistivity values are obtained that are interpreted in the same manner as DC systems. The method can be a relatively rapid and inexpensive reconnaissance exploration tool where audio frequency ranges are relatively strong and continuous.

Telluric methods measure the natural electrical currents that flow on or near the earth's surface in large sheets. Variations in these currents affecting resistivity measurements may be caused by changing geologic conditions or, presumably, encountering a hydrothermal system. Measurement of the telluric field takes place at two stations. By moving a field station around the fixed position of the base station, horizontal resistivity variations can be plotted.

Controlled source electromagnetic methods utilize signals produced by a transmitter operating at selected frequencies in addition to the natural currents. Resistivity measurements at different depths can be obtained by changing the distance between the transmitter and receiver or by varying the frequency used.

Self-potential measurements are another natural field technique that may have application in exploration for hydrothermal reservoirs. Surveys in several areas with known reservoirs show an anomalous electrical direct current field is present, believed to be associated with fluid convection systems.

Electrical geophysical techniques, by themselves, are not a well-defined path to instant geothermal exploration success. Ball, et al., (1979) suggest that the use of electrical methods of all kinds is not well understood in geothermal exploration in spite of their routine application by the industry. They have been used with some confidence in mapping faults, fractures, and zones of alteration and are, therefore, considered almost fundamental in the location of development and some exploration wells. So many different techniques and systems exist, however, that there is confusion over their application under varying geologic conditions, often to the extent that inefficient field procedures and uncertain applications result. As with many other exploration tools, they are excellent supplements to the target definition process. Their continued use with refinements in instrumentation and interpretive techniques will lead to greater confidence and cost-effectiveness in geothermal prospecting.

Passive Seismic Methods

Microearthquake surveys rely on natural phenomena such as earthquakes and landslides or remote random explosions to generate a measurable energy field that may be recorded at instrument stations in a number of locations throughout a region. The instruments are sensitive to low level seismic vibrations called microearthquakes. Investigators are persuaded that detection of persistent "swarms" of microearthquake activity is an effective exploration tool to locate active faults

[Jaksha, et al., (1980)], active fault zones in a geothermal area that are serving as conduits for hydrothermal fluids [Ball, et al., (1979)], and shallow molten magma bodies moving in the upper and middle crustal levels of the earth [Sanford, et al., in Riecker (1979)]. On the other hand, in areas where young, presumably active faults are located, the absence of microearthquakes may imply that strain energy at shallow depths is being absorbed by a hot, not necessarily molten body that encourages rock adjustments by creep rather than brittle failure [Newton, et al., (1976)]. A perceived disadvantage to microearthquake surveys is that observations must usually take place over a number of months in order to develop meaningful data.

Ground noise surveys have determined that high ground noise levels that are measurable with acoustic devices are associated with many geothermal fields. These noises are attributed to fluid movement in a hydrothermal convection system. Whether this feature is unique to hydrothermal fields or is relatively ubiquitous will require additional analysis.

Temperature Gradient Verification Methods

Technically, procedures involving temperature gradients and heat flow measurements fall within classifications assigned to geophysical exploration methods. Of all the assessment techniques used in geothermal verification, however, thermal methods rank at the top in terms of application and perceived effectiveness [Nielson (1979)]. Therefore, in a discussion of exploration procedures, they warrant independent discussion.

The increase of temperature with depth is the earth's geothermal gradient. Thermal energy moving to the earth's surface by conduction of heat through solid rock is termed heat flow.

The geothermal gradient is obtained by drilling a hole and taking temperature measurements at various levels. The procedure can be relatively simple and inexpensive when profiles from shallow holes, less than 500 ft (150 m), will satisfy the requirements of the exploration program. In these instances a truck mounted rig is used to drill a hole within which a small diameter pipe filled with water is inserted and allowed to reach equilibrium with the temperature of the surrounding rock. Because of the small pipe diameter, convection currents do not form, so the water temperature at various levels is the same as the rock that enclosed it. Temperature is measured by a thermister probe on a cable, the results of which are plotted to establish a gradient for the hole. Cuttings and cores of the rocks penetrated by the drill are analyzed to estimate the thermal conductivity or heat flow of the region.

Thermal gradient wells are used in geothermal exploration primarily because they can directly detect heat. Other exploration methods can only indirectly suggest that heat may be present in the subsurface. Shallow wells are commonly used to confirm a prospect after other procedures have narrowed the focus. Many geothermal exploration programs incorporate thermal gradients from deeper and more expensive wells as a basic exploration tool in regional analysis. These are considered cost-effective means to eliminate areas of low thermal gradient and heat flow so that resources can be concentrated on more promising targets, particularly in the search for high temperature hydrothermal reservoirs. Temperature measurements from probes at very shallow depths, usually less than 3 ft (1 m) are used to establish the productive limits of known high temperature geothermal reservoirs.

It is not always necessary to drill temperature gradient holes for a specific program. Often, definitive data are available or can be obtained at less cost by using holes drilled for other purposes. Thousands of wells are drilled annually in the U.S. for such commodities as oil, gas, uranium, coal, base metals, other minerals, water, stratigraphic information, and many other purposes. Many of these, specifically the oil and gas tests, have had their temperatures "taken" whenever mechanical logs were run.

Governmental entities such as USGS, BIA, and State Water Engineers commonly measure temperatures from producing water wells. Farmers and ranchers may not object to temperature probes of their water wells. Obtaining these data may not be as accurate and reliable as drilling a controlled well for the same purpose, but if it is available it represents an inexpensive and rapid means to accumulate a geothermal base.

Careful consideration of the geology and hydrology is a necessary prerequisite to extrapolating thermal gradients to possible reservoir depths. Rock type, permeability, induration, and fluid saturation can influence the results of thermal probles. The movement of shallow ground water across the area of interest, for instance, can carry away, displace, or mask the conductive heat flow or convective mobility of even a strong thermal anomaly.

Geochemical Verification Methods

The premise of geochemical analysis in geothermal exploration is that the solubility of various elements or ratios of elements in water is temperature dependent, that the concentrations become established within a geothermal reservoir, and that these ratios will not change as the water moves to the well or spring where it is sampled. Plotting chemical concentrations or ratios against the temperatures encountered in known geothermal reservoirs establishes empirical curves that can be used to relate chemical concentrations found in sampled waters to the temperature of the reservoir they originated in. These component concentrations or ratios that can be related to subsurface temperatures are called geothermometers, and the evaluation technique is known as geothermometry.

Chemical geothermometers may be quantitative or qualitative. Quantitative methods are used to calculate or predict specific subsurface reservoir temperatures, fluid flow patterns, recharge sources of the reservoir, to indicate the type of reservoir rock, and to provide useful data on a number of other important parameters of the geothermal system. Qualitative geothermometry is commonly applied in regional geothermal exploration efforts to locate "blind" or hidden convection systems that are components of nonthermal waters.

The use of geothermometers is based upon the distinct chemical character of certain waters depending upon their initial source. White (1957) divides natural waters into juvenile, magmatic-volcanic, meteoric, oceanic, metamorphic, and connate classifications. These waters are not independent but are related through a number of geologic processes. Ocean water deposited with sediment, for instance, over time and as the sediment becomes indurated, becomes connate or fossil water. If the rock is subjected to intense pressure and heat, a process known as metamorphism commences causing interstitial water to react with the containing rock materials or to be released from hydrated minerals. This water becomes metamorphic water and contains an abundance of components derived from the host rock.

Juvenile waters are released from a primary magma body and contain elements that solidify at relatively low temperatures. These waters are commonly enriched with volatiles such as hydrogen sulfide (H_2S) and carbon dioxide (CO_2), in elements such as lithium (Li), fluorine (F), boron (B), sulfur (S), and rare earths. Magmatic-volcanic waters are similar to juvenile except the magma is derived from the melting of rock types that include sediments and metamorphics as well as volcanics. These waters are likely to contain significant ratios of silicon (Si), arsenic (As), and chlorine (Cl). They are low in calcium (Ca) and magnesium (Mg) and lack organic compounds.

Meteoric water is water that is derived from the atmosphere (rain, snow). It normally has a high potassium (K) to sodium (Na) ratio, contains Ca and abundant organic compounds. Ocean water is rich in Cl, Mg, Na, and K. Connate water, ancient ocean water deposited with the sediments, has concentrations of iodine (I), nitrogen (N), B, Si, and certain compounds such as ammonia (NH_3) and CO_2.

Isotopes and rare gas consituents of geothermal fluids have been used to indicate sources of recharge, time of circulation, fluid mixing, age of the fluids and subsurface temperatures, as well as indicating the original source and environment of the water. Tritium, for instance, with a half life of 12.5 years, can be detected in meteoric water that has circulated within a hydrologic system in the past 50 years. It, and other isotopes such as deuterium and oxygen-18, have been used with chemical geothermometers to calculate the temperature history of a reservoir and prove that local meteoric water dominates the recharge and is the source of most geothermal systems.

Analysis of known hydrothermal regimes show volcanic systems with heat originating from recent igneous intrusions and dominated by hot water or steam to be distinguished from nonvolcanic systems in which the heat source is normal or elevated regional heat flow where water is heated by deep circulation along faults or by their position in broad downwarped sedimentary basins. Because most high temperature geothermal reservoirs are associated with volcanic activity and many of these have been developed, their chemical makeup has been thoroughly studied and is reasonably well understood; however, the chemical makeup of fault controlled and sedimentary systems is poorly understood [Truesdell (1975)].

Chemical differences between waters with diverse sources, contained in rocks of varying constituents with elements that become soluble at known or theoretical ranges of temperature and pressure are the parameters that geothermal geochemistry uses to estimate subsurface temperatures. Chemical indices based on trace constituents of spring fluids and well discharges, their deposits, altered rocks, soils, and soil gases form the models of the interaction of geothermal fluids with reservoir rocks. Some of the assumptions that form the basis for geochemical analysis include: 1) temperature dependent fluid reactions occur at depth, 2) all constituents (elements) involved in a temperature dependent reaction are sufficiently abundant, 3) water-rock equilibrium is established at depth, 4) water-rock equilibrium is attained at the reservoir temperature, 5) the water sampled is the same composition as that at depth, and 6) dilution of deep hot water with shallow cold water does not occur. The latter is critical to evaluation of lower temperature geothermal regimes in terms of accurate definition of subsurface temperatures, although not necessarily detracting from constituent identification suggesting a subsurface hydrothermal reservoir.

A number of constituents or ratios of constituents can be used to estimate minimum reservoir temperatures. Those in most general use in geothermal exploration programs are the fluid content of SiO_2, and the relationship between Na, K, and Ca. These, and several modifications to incorporate corrections for non-uniform conditions have been quantified to yield numerical estimates of subsurface thermal values. The equations used are shown in Table 5.

Geothermometer components are necessarily not in equilibrium under surface conditions, and special care in sampling techniques must be taken to preserve them for accurate laboratory analysis. Geochemical investigations depend on the accurate chemical and isotopic analysis of natural fluids and on laboratory measurements of the properties of chemical substances over a range of temperature and pressure. Results should not be used alone but should be supplemented with geological and geophysical data. Particularly in evaluating lower temperature regimes geochemical methods alone are subject to too many variables to be used solely to condemn or confirm a geothermal target.

Exploratory Well Drilling

The only way to confirm the existence of a usable geothermal reservoir is to drill a well. All of the verification procedures described above lead to a single decision: whether or not to drill the exploratory well. The geological, geochemical, geophysical and thermal gradient techniques simply refine observed and assumed phenomena to a predictive model that is incomplete without the well. Drilling the well will probably be the greatest expense of the entire exploration program, and there is no guarantee it will be successful.

The drilling program selected will depend primarily on depth, rock type, and temperature. The costs and level of drilling program sophistication involved for a deep well evaluating a high temperature hydrothermal regime in a volcanic province for electrical generating purposes is far higher than that required for low to moderate temperature regimes encountered in a sedimentary section at shallower depths that will be used for space heating. Equipment needed can range all the way from cable tool rigs used for water well drilling with practical depth limits of about 2,000 ft (600 m), through truck mounted rotary rigs that can drill to about 4,000 ft (1220 m) in most areas, to standard oil field rotary rigs of medium size (15,000 ft/4,575m) to large size (30,000 ft/9,150 m).

Finally, it should be noted that in some areas drilling an exploratory well may be the fastest, least expensive and most definitive method to evaluate a geothermal prospect. If available data from nearby water or oil wells supplemented by reconnaissance geology suggest that a usable resource exists at shallow depths in the area of interest, there may be no need for refinement procedures. One or two relatively inexpensive wells drilled with a truck mounted rig can confirm or condemn the prospect.

Table 5. Equations for geothermometers
[Truesdell (1975)]

Silica Geothermometers (SiO_2 in ppm)*

Quartz, adiabatic cooling ($\pm$ 2°C from 125-275°C):

$$t°C = \frac{1533.5}{5.768 - \log SiO_2} - 273.15$$

Quartz, conductive cooling ($\pm$ 0.5°C from 125-250°C):

$$t°C = \frac{1315}{5.205 - \log SiO_2} - 273.15$$

Chalcedony, conductive cooling:

$$t°C = \frac{1015.1}{4.655 - \log SiO_2} - 273.15$$

Na/K Geothermometers (Na, K in ppm)

White and Ellis (see text) ($\pm$ 2°C from 100-275°C):

$$t°C = \frac{855.6}{\log (Na/K) = 0.8573} - 273.15$$

Fournier and Truesdell (1973):

$$t°C = \frac{777}{\log (Na/K) + 0.70} - 273.15$$

NaKCa Geothermometer (Na, K, Ca in moles/liter)

Fournier and Truesdell (1973, 1974):

$$t°C = \frac{1647}{\log (Na/K) + \beta \log (\sqrt{Ca}/Na) + 2.24} - 273.15$$

$\beta = 4/3$ for $\sqrt{Ca}/Na > 1$ and $t < 100°C$

$\beta = 1/3$ for $\sqrt{Ca}/Na < 1$ or $t_{4/3} > 100°C$

*Data from Fournier (written communication, 1973)

COST ESTIMATES, TIME FACTORS, AND ENVIRONMENTAL IMPACTS

Cost estimates, time factors, and environmental impacts are all a function of the scale of the geothermal exploration program. The search for a high temperature reservoir for use in generating electricity will normally cost far more, take greater time, and have considerably different environmental effect than the program seeking usable low temperature regimes. Because each geothermal occurrence is somewhat different from all the rest, it would not be possible to list every feature of geology and geography that contributes to cost, time, and environmental considerations.

A geothermal verification program should be discerned as a data gathering system involving a series of step by step progressions. Beginning with little or no information, the objective is to obtain sufficient definitive material from each phase of the program to justify a decision to drill an exploratory well. Each succeeding step or phase logically follows favorable evaluation of the preceeding ones. Each higher level phase ordinarily involves acquisition of more specific, detailed, and technically objective data, which cost more to obtain, take longer to evaluate, and may present a greater possibility for adverse environmental effect.

Flexibility is a key element of any planned geothermal exploration program. A program phase appropriate in one area of geologic province may not be necessary or definitive in another. Unanticipated problems may arise that require techniques to resolve them that were not initially planned. Conversely, a procedure may generate sharply defined data that eliminate the need for a planned subsequent phase.

A major consideration in terms of a program's flexibility is the capacity to terminate it. Each program phase should be designed to supplement and compliment data obtained by previous phases. Evaluation must be a continuing part of program monitoring. If data are not suggesting or confirming a geothermal reservoir model, analysis indicates that a usable reservoir does not exist, and no reasonable methodology can be proposed to contradict the negative evaluation, the decision should be made to conclude the effort.

Table 6 shows a proposed decision matrix for geothermal reservoir verification, by phase. It is presumed for purposes of discussion that the program is designed to evaluate a hydrothermal prospect in the upper-moderate temperature range of about 302°F (150°C). A preliminary realistic assessment has determined that a planned program must be site-specific for an Air Force installation that could use water in sufficient volumes for some direct applications at a temperature in excess of 158°F (70°F) at the wellhead. In other words, the cut-off "grade" as to whether an exploration program would be considered successful would not necessarily be confined to the "ideal" higher temperature the program is designed to find. A project that was completely successful could make the entire installation energy independent for its non-transportation needs. Any lower temperature and volume encountered should be closely examined for a specific application such as supplementing the heat for a single hangar or building.

The exploration procedures described in Table 6 culminate in drilling an exploration well costing $500,000. Costs to this decision point would range between $50,000-300,000, probably averaging about $200,000.

Table 6. Proposed sequenced geothermal exploration program: time, costs and environmental impacts

Phase	Description	Time Required Phase Task	Cost Per Phase Task In $1,000's	Environmental Impacts (Notes)
I	**Literature search** Analysis, preliminary report	2-4 months	$12-25	None. (*Note:* Consulting geologist @$200-$400 per day. Estimate average of 3 months & $15K)
II	**Aerial photos**	1-3 months	$2-15	None. (*Note:* Some or all of the costs of interpretation may be included in Phase I. Estimate average of 1.5 months & $3K)
	1. Acquisition, 2,000 square miles, black & white			
	a. If ordered from a public agency	1-2 months	$1-2	
	b. If flown for project	1 month	$5-7.5	
	2. Interpretation	1.5 months	$7.5	
III	**Regional reconnaissance**	1-6 months	$5-75	Minimal. If gravity survey is required, it may be necessary to cut survey line through any timber or brush. (*Note:* Some or all of the costs indicated by * may be included in Phase III, 1. Tasks in brackets may not be required for site-specific GT verification. Estimate 3 months & $20K for Tasks 1, 2, 3, and 8)
	1. Regional geology	1-4 months	$5-25	
	2. Geochemistry of springs, etc. ($100/smpl analysis; 25 smpl)	1-2 months	$2-5	
	3. Thermal gradients, existing wells	1-2 months	*	
	(4) Check land status, mineral title, water rights, regulations	1 month	$1-5*	
	(5) Aeromagnetics ($25/line mi; 100 mi.)	2-3 weeks	$2.5	
	(6) Gravity survey ($45/station; 100 stations)	1 month	$4.5	
	(7) Microearthquake survey	6 months	$30	
	8. Preliminary modeling	1 month	$5*	
IV	**Detailed investigations**	1-6 months	$30-180	Measurable. May be necessary to cut survey lines through timber or brush and bulldoze trails for seis trucks and truck mounted rigs. About 1,000 sq. ft. needs to be cleared for shallow TG wells & explosive seis rigs. Explosive seis has potential to damage nearby water wells & structures (*Note:* full fledged Phase IV will come close to needing largest $. Only significant savings will be if active seismic not used. Add consultant fee for oversight, about $25K for 5 months. Estimate about $150K. ME *could* be effective preliminary site specific tool under appropriate conditio[illegible])
	(1) Microearthquake survey	6 months	$30	
	2. Gravity ($45/station, 50 stations)	1 month	$2.25	
	3. Electrical resistivity ($1,200-$2,000/line mi w/interpretation; about $1,000/day; 20 mi)	1 Month	$30	
	4. Active seismic ($3-$8,000/line mi. w/interpretation, 15 mi. required)	2 months	$90	
	5. Drill temp grad wells ($3-$50/ft; 10 wells @300/ft. ea @$10/ft)	1.5 months	$30	
	6. Detailed geologic mapping	1 month	$7.5	
	7. Geological recommendation	1 month	$7.5	
V	**Exploratory well** ($50-$150/ft or day rate of $4,000-$7,000 for for wells 5,000-12,500 ft deep, assume 9,000 ft turnkey w/drill stem tests, logs, cores, included)	3 months	$500	Can be significant. High standard road required. 1-2 acres cleared for drill pad. Operates 24 hrs/day, noise a problem in populated areas. (*Note:* drill costs escalate dramatically at depths greater than 10-12,000 ft & with [illegible] [illegible]

SUMMARY

Geothermal exploration begins with a knowledge of the resource and what it is capable of doing relative to fuel substitutions. Once it has been determined that there are applications, a program must be designed to explore for a usable reserve. The program may be regional in scope, encompassing 2,000 to 10,000 square miles (3,200-16,200 km^2) or more where the intent is to locate the resource and acquire through lease or purchase the land it occupies. Or, the program may be site-specific to evaluate and verify the geothermal resource potential of lands already owned or legally controlled.

The search usually consists of a regional investigation followed by detailed analysis of local anomalies if these are encountered. The purpose of the regional exploration phase is to identify geologic parameters that are considered favorable for establishing a geothermal resource and locate target areas that justify more detailed investigations. If the examination is site-specific, the regional analysis is appropriate to establish the geologic environment and framework relative to adjoining areas. This will reduce the risk of omitting or failing to consider data important to the predictive geothermal model. If regional evaluations are favorable, more sophisticated, costly, and detailed procedures are implemented to form the basis for a decision of whether to drill an exploratory well. If the decision to drill is reached, the exploration techniques will have also determined the optimum location for the well.

Exploration sequencing starts with techniques that are low in cost and aerially extensive and proceeds to local prospects requiring higher cost and more definitive methods. Literature searches gather pre-existing information about the geology, geophysics, geochemistry and geothermal resources for evaluation. This phase may be supplemented with acquisition of aerial photography in order to locate and refine surface expressions of structure and petrology important to the exploration program. Reconnaissance exploration procedures are then commenced in order to verify and expand geologic leads by on-site observations, collection of well and spring samples for chemical analysis, and obtaining whatever thermal measurements were made in wells drilled for other purposes in the region. If necessary and appropriate various geophysical techniques may be employed to determine gross crustal relationships and thickness.

After evaluation of the regional data and with a favorable decision to proceed, more detailed and more expensive geological and geophysical surveys are initiated in target areas. These may include electrical resistivity surveys, seismic refraction and reflection techniques, drilling thermal gradient holes, and detailed geological mapping.

When the predictive geothermal reservoir model is as complete as reasonable and cost-effective procedures and interpretation permit, the assembled data are evaluated and a decision reached of whether to drill a well. Drilling the exploratory well is the only way to confirm or disprove the existence of the assumed geothermal reservoir.

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Appendix A

Geothermal Data Sources

Some sources for geothermal data are described below. Within the office or agency those with specific geothermal expertise should be contacted. Also, it is not uncommon for those in one office to interact with others with specialized geothermal information on the area of interest, so appropriate questioning may expand the data base.

U. S. Geological Survey (USGS)

Provides a broad range of geothermal information in the form of maps, published technical reports, unpublished open-file reports, and consultation with geothermal resource investigators. Many of the larger cities have USGS branch offices that may offer assistance in locating geothermal data or resource personnel. The main USGS offices for operations in the eastern part of the U.S. are in Reston, Virginia, while the western U.S. is administered out of the Denver Federal Center in Colorado and Menlo Park, California. The USGS Area Geothermal Supervisor in Menlo Park oversees geothermal leases on all federal lands and could provide information about private firms with leases in the area and federal regulations.

State Universities (and larger privately endowed colleges)

The earth scientists in these schools can be excellent sources for data. Some of these instructors may have investigated geothermal resources in the area of interest and their students may have prepared unpublished theses relating to the subject. Their libraries offer an inexpensive and rapid means to examine geothermal literature. Some of the eastern schools have DOE contracts to assist the public in geothermal resource assessment.

U. S. Department of Energy (DOE)

DOE offices are found in most major cities. Few of these are involved with geothermal resources, although they may provide assistance in reaching DOE personnel in the Geothermal Division in Washington. The Department of Energy, Division of Geothermal Energy is the major source of federal funding for public and some private geothermal resource investigations.

National Oceanic and Atmospheric Administration (NOAA)

This federal agency with offices in Boulder, Colorado, is publishing maps by state and region outlining known and inferred geothermal resources.

State Geological Surveys

These may also be identified as a State Bureau of Mines and Minerals or as an Office of the State Geologist. These agencies will probably have one or more of their personnel assigned to evaluate the state's geothermal potential. They can also be of assistance in identifying and locating germane publications.

State Energy Offices

Many states are involved with resource assessment programs sponsored by the federal government. If there are geothermal programs, this office is likely to be involved. This is usually the best agency to obtain regulatory information from.

State Land Offices

In states that own significant portions of lands within their borders, the land office is often a valuable source of information concerning the leasing and exploration activities of others.

State Engineer (or Water Division) Office

Particularly in western states, the State Engineer can be a source of information on geothermal activity as well as state requirements for drilling geothermal wells.

Geothermal Resources Council
P. O. Box 98
Davis, California 95616

This is a private entity devoted to disseminating data derived from professional persons working in the geothermal field. They would be useful in helping identify those familiar with the area as well as locating published data.

EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, Idaho 83401

This firm is a prime contractor to DOE for matters that include technical, professional and financial support for a number of states that are defining and development their geothermal resources.

New Mexico Energy Institute (NMEI)
P. O. Box El, New Mexico State University
Las Cruces, New Mexico 88003

This entity, with contracts from DOE, the Four Corners Regional Commission, and the New Mexico Energy and Minerals Department, provides regional economic and analytic modeling for state planning work being conducted in the Rocky Mountain states. The program is engaged in developing realistic assessments of identified geothermal sites and defining the necessary prerequisites for their commercial use.

Oregon Institute of Technology (OIT)
Klamath Falls, Oregon 97601

Provides user technical assistance and regional planning support in the northwest.

University of Utah Research Institute (URRI)
391-A Chipeta Way
Salt Lake City, Utah 84108

Contracted by DOE to conduct and coordinate a number of geothermal resource definition programs. Provides limited technical assistance.

Los Alamos National Laboratory (LANL)
P. O. Box 1663
Los Alamos, New Mexico 87545

Conducts research, development and demonstration into Hot Dry Rock (HDR) systems. Has extensive expertise in exploration, drilling and production. Is providing world-wide outreach on HDR technology. Provides limited technical assistance for direct heat hydrothermal applications with DOE funding.

Sandia National Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87185

In addition to other resource investigations, Sandia's Geo Energy Technology Department addresses geothermal drilling and completion technologies and conducts the nation's Magma Energy Research Project.

National Aeronautics and Space Administration (NASA)

Their Technology Applications Center (TAC) has access to computer data bases containing geological/geothermal information.

There are undoubtedly a number of other entities that could be identified in the geothermal field, but the above are representative of those that are generally involved, easily accessible and public information oriented.

Distribution:

HQ USAF/LEY
The Pentagon
Washington, DC 20330

HQ USAF/LEE
The Pentagon
Washington, DC 20330

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The Pentagon
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The Pentagon
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The Pentagon
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AUL/LSE 71-249
Maxwell AFB, AL 36112

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Andrews AFB, DC 20334 (3)

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Andrews AFB, DC 20334

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Andrews AFB, DC 20334

HQ AFSC/DEEB
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HQ USAFA/DE
USAF Academy, CO 80840 (3)

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USAFA/DFP
USAFA Academy, CO 80840

USAFA/DFEM
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HQ TAC/DE
Langley AFB, VA 23665 (3)

HQ SAC/DE
Offutt AFB, NE 68113 (3)

HQ SAC/DEPD
Offutt AFB, NE 68113

HQ MAC/DE
Scott AFB, IL 62225 (3)

HQ ATC/DE
Randolph AFB, TX 78148 (3)

HQ ATC/DEE
Randolph AFB, TX 78148 (2)

HQ ATC/DEV
Randolph AFB, TX 78148 (2)

HQ AAC/DE
Elmendorf AFB, AK 99506 (3)

HQ AFLC/DE
Wright-Patterson AFB, OH 45433 (3)

HQ USAFE/DE
APO New York 09012 (3)

HQ PACAF/DE
Hickman AFB, HI 96824 (3)

AFOSR/CC
Bolling AFB, DC 20332

AFWAL/POE
Wright-Patterson AFB, OH 45433 (2)

DTIC/DDA-2
Cameron Station
Alexandria, VA 22314 (2)

OASD (MRA&L)/EES
The Pentagon
Washington, DC 20301

USA/CERL
Champaign, IL 61820

USA/DAEN-RDM
The Pentagon
Washington, DC 20301

USA FESA
Ft. Belvoir, VA 22060

AFIT/Library
Wright-Patterson AFB, OH 45433

AFIT/DE
Wright-Patterson AFB, OH 45433

USN NCEL
Port Hueneme, CA 93041

NAVFAC/Code 1113 (T. Ladd)
200 Stovall Street
Alexandria, VA 22332

HQ AFESC/DEB
Tyndall AFB, FL 32403 (4)

HQ AFESC/TST
Tyndall AFB, FL 32403

HQ AFESC/RDVA
Tyndall AFB, FL 32403

HQ AFESC/RDVA
Tyndall AFB, FL 32403 (15)

HQ AFESC/RDV
Tyndall AFB, FL 32403

AFATL/DLODL
(Tech Library)
Eglin AFB, FL 32542

ALO/ERTD
Department of Energy
P. O. Box 5400
Albuquerque, NM 87115 (5)

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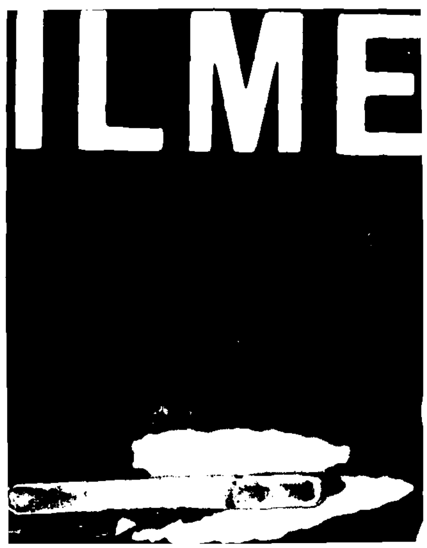
4300	R. L. Peurifoy, Jr.
4400	A. W. Snyder
4500	E. H. Beckner
4700	J. H. Scott
4710	G. E. Brandvold
4715	R. H. Braasch
4720	D. G. Schueler
4740	R. K. Traeger (5)
4741	J. R. Kelsey
4743	H. C. Hardee
4743	L. Riddle
4746	B. Granoff
4747	R. K. Traeger, Actg.
4748	B. E. Bader
4750	V. L. Dugan
5541	W. C. Luth
3141	T. L. Werner (5)
3151	W. L. Garner (3)
3154-4	J. Hernandez (25) (for DOE/TIC)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